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Development and application of a water budget model for lake level fluctuation, Goose Lake basin, Oregon-California

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A water budget model was developed to estimate year-end lake volumes of Goose Lake, Oregon-California, to determine whether an accurate reconstruction of lake volumes/levels could be made with several synthesized or partial volumetric components. Components evaluated were the lake level/volume observations, precipitation, streamflow, and evaporation during the data-rich study period, 1946 to 1975. By regressing estimated year-end volumes against actual volumes (using actual volumes as the input at the beginning of each year) a correlation coefficient of 0.97 was obtained. By letting the series' year-end volumes be substituted for the following years'

antecedent volumes a systematic error was created, identical in time and degree to irrigation consumptive use in the basin. The consideration of this additional component improved the self-generating series. The interaction of the components described by the model was then fed into a reconstruction model which used regression equations relating precipitation and runoff to annual tree-ring width indices. In this manner, a long-term synthetic runoff and precipitation record was developed for the basin for the period 1422 to 1964. Trends in the model output for the recent period (1830 to present) closely parallel recorded observations of lake level/volume although the range of reconstructed volumes was not as extreme as actually occurred. Nevertheless, the "actual" versus "synthesized" lake level series (1946 to 1964) were fairly well correlated (r=0.75), being significant to the 0.99 level. The study shows that tree rings are useful in the reconstruction of hydrologic and climatologic phenomena and are especially sensitive to changes in available water supply but do not show the high interannual variation seen in both precipitation and streamflow. Additionally, the tree ring record appears to be more sensitive to drought than to dry conditions in the basin and is therefore not well suited to determining the recurrence interval of high-water conditions.

Development and Application of a Water Budget Model for Lake Level Fluctuation, Goose Lake Basin, Oregon-California.

by

DOUGLAS DANIEL NEBERT

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TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

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CHAPTER I

INTRODUCTION

Throughout the intermontane region of the western states are scattered playas and remnant water bodies where once stood extensive pluvial lakes. The record of climatic variability left behind by these lakes has intrigued many of the explorers in search of suitable land and water resources required by westward expansion.

I. C. Russell, pioneer reconnaissance geologist, said of this enigmatic closed-basin phenomenon:

> The study of these natural pluviometers teaches that the fluctuations of the lakes of the Great Basin during the last few years are but a continuation of the climatic oscillations that reached a maximum at the time Lake Bonneville and Lake Lahontan were brimming (Russell 1884, p.457).

In the last several years climatic conditions have caused many closed-basin lakes such as the Great Salt Lake, Utah, and Malheur-Harney Lake, Oregon, to fill to near-record levels. This is due to three wetter and possibly cooler than normal years in a row in the Great

Basin, leading to excess runoff and decreased evaporation, and resulting in above normal lake volumes.

The calculated recurrence interval of lake-level extremes has traditionally been limited to the period of observation of lake-levels which, at its best, extends into the mid-1800's. A need exists to evaluate the recent record of lake-level oscillation and, if possible, to reconstruct former lake levels to assess more accurately the recurrence interval of both drought and water surplus phenomena. Can year-end volumes of a closed-basin lake be predicted with accuracy if only a limited number of inputs and losses are known or can be derived? If so, can a longer-term environmentally sensitive series be used to reconstruct the water balance of the system on an annual basis?

The premise demonstrated herein is divided into two logical steps. First, it will be shown that a reliable year-end lake volume can be derived for a closed-basin lake given actual or partially synthesized inputs and losses from the lake for a certain year. Second, it will be demonstrated that given the highly similar nature of recent annual precipitation, streamflow, and tree-ring time series, a relative reconstruction of past lake levels is possible using the basin tree-ring record to drive the water budget model. A probability analysis of the synthetic record is then presented and compared with that of the present period.

The scope of this thesis is limited to the analysis of the Goose Lake basin, a closed basin located on the California-Oregon border. The control period for water budget model building is between water years 1946 and 1975 during which an abundance of lake-level records were kept. The water budget model presented relates year-end lake volume to basin parameters such as precipitation, evaporation, streamflow, and antecedent lake volume. In this manner, a record of lake-level fluctuation is constructed given one or more of the annual variables. The precipitation and streamflow annual series are then correlated with tree-ring series for the common period, 1913 to 1964, demonstrating sensitivity to both high and low water events. Synthetic runoff and precipitation series are then joined as primary lake inputs against an evaporative loss and a long-term lake volume record is constructed for the years 1422 to 1964. The synthetic record is then checked for sensitivity against historical knowledge of the lake.

The concept embodied in this thesis is an outgrowth of a paper written to compare precipitation and runoff for a basin in Oregon and expanded into an intriguing examination of Goose Lake. The relative abundance of data for this basin was the main reason for its selection over other basins in the state, although the techniques applied here should be useful in determining similar oscillation histories for other closed-basin lakes in the region.

All measurements of temperature, distance, and volume will be given in English rather than metric units. Since it is the practice of both the U. S. Geological Survey and the National Weather Service to report data in English units, their policy is adopted throughout this thesis.

CHAPTER II

BASIN CHARACTERISTICS

Geographic Situation

The Goose Lake drainage basin, the defined study area for this thesis, is located on the California-Oregon border twenty miles west of the states' common junction with Nevada. The basin is centered about 42° 05' North Latitude, 120° 25' West Longitude, and lies wholly within Lake County, Oregon and Modoc County, California (See Figure 1).

The basin is approximately 1100 square miles in area, with a slightly elongate profile, north-south [(1)]. The basin has a maximum length of 53 miles and a maximum width of 36 miles. Nearly 80 percent of the basin lies in Oregon, whereas the remaining 20 percent is in California. The major drainage area is on the Oregon side and the lake itself lies at the southern end of the basin with a surface area of between 120 and 194 square miles, varying exponentially with volume.

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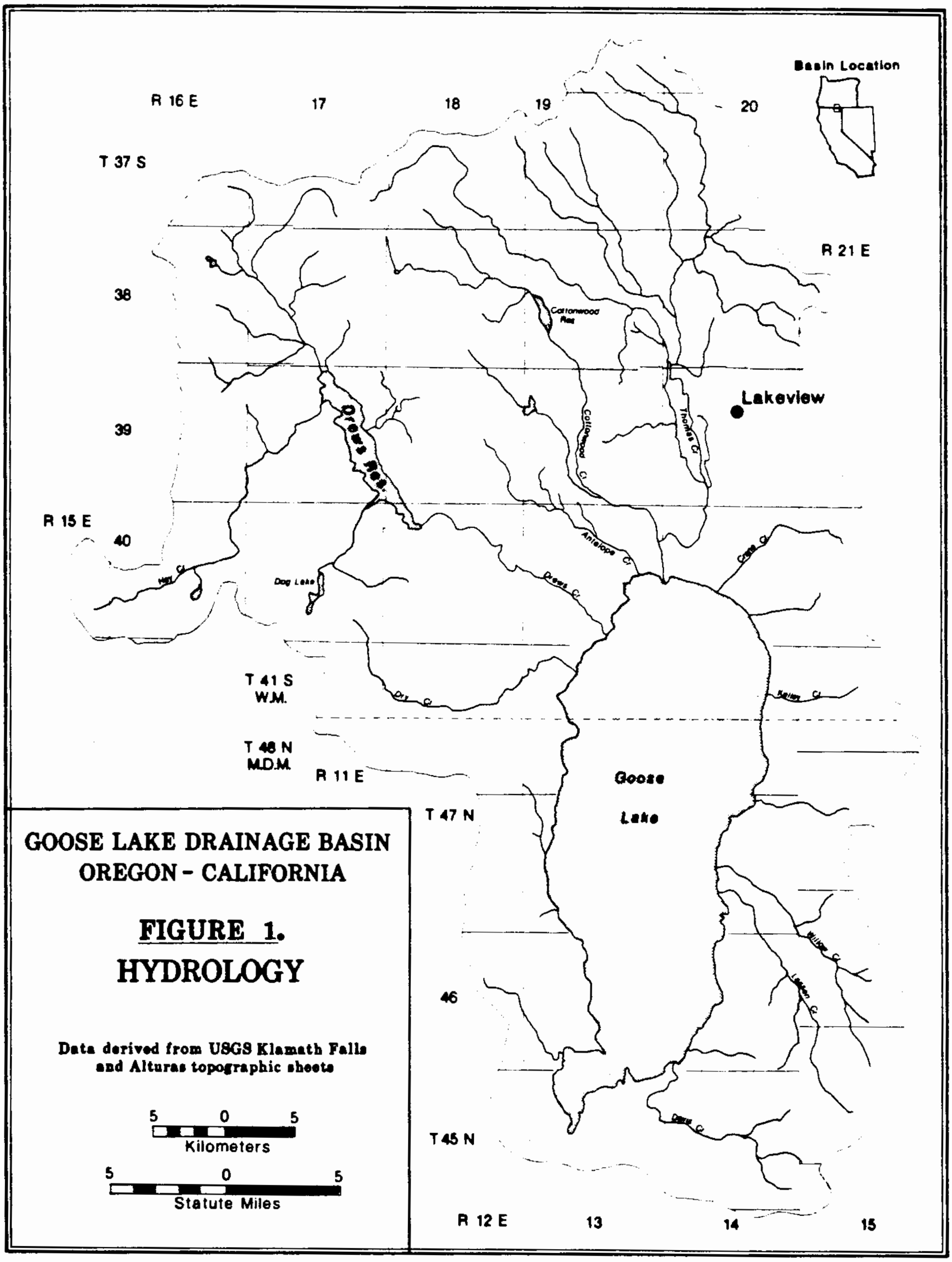
(1) The entire basin is covered by USGS topographic maps. The Klamath Falls and Alturas 1:250,000 scale Quadrangles are the best for orientation. The Oregon Public Land Survey System is based on the Willamette Base and Meridian; California's uses the Mt. Diablo Base and Meridian.



GOOSE LAKE DRAINAGE BASIN
OREGON - CALIFORNIA

FIGURE 1.
HYDROLOGY

Data derived from USGS Klamath Falls and Alturas topographic sheets

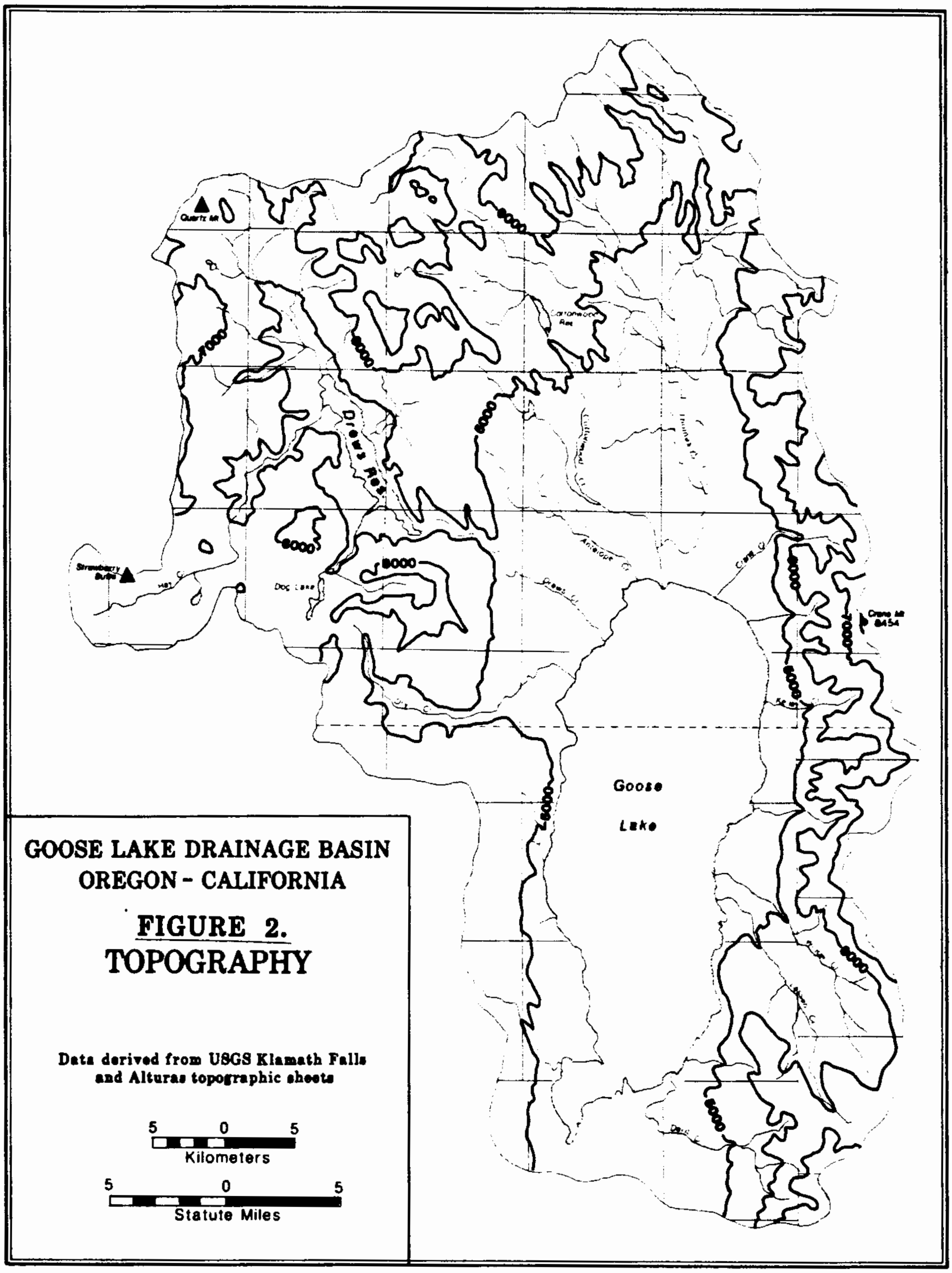
Physiography

The drainage basin lies in a transitional zone between the High Cascades to the west and what is commonly known as the Basin and Range to the east. The fault block topography common to the basin and range immediately to the east and north is not as pronounced within the basin, although a severely dissected fault-line scarp marks the basin's eastern margin. On the other hand, volcanism more common to the High Cascades has also occurred in the basin. Geologic details are discussed further in the next section.

Located in gently rolling terrain consisting of disected volcanic strata, the basin has an average elevation of 5000 feet. The highest elevation can be found on Crane Mountain at 8454 feet, whereas the lowest surface elevation is the surface of Goose Lake at approximately 4700 feet. The steepest terrain is found near Crane Mountain in the Warner Mountains, with a grade approaching 17 percent, as derived from topographic maps. The terrain with the least gradient is that surrounding the lake and extending several miles north. Hills of intermediate grade (approximately 10 percent) define the northern and western surface hydrologic divide and are known as the Fremont Mountains (See Figure 2).

Geologic History

Goose Lake Valley lies within a complex tectonic region



GOOSE LAKE DRAINAGE BASIN
OREGON - CALIFORNIA

FIGURE 2.
TOPOGRAPHY

Data derived from USGS Klamath Falls and Alturas topographic sheets known as the Basin and Range geologic province. Russell (1884) made some remarkably astute observations of the region around Goose Lake, describing the tectonic features of southern Oregon:

> A force or series of forces, the power and extent of which are utterly beyond the limits of our conception, was brought into action over a region of at least 250,000 square miles in area, and broke the earth's crust into thousands of fragments, which were depressed and buried, or upheaved into mountain ridges (1884:451).

The region within the study area is characterized by prominent NNW to SSE trending normal faults caused by regional EW extensional stresses and rotation of most of the Pacific Northwest during the last 17 to 30 million years. Some right-lateral faulting might be inferred to the northwest of Goose Lake in the vicinity of what is today Drews Reservoir. In fact most of the stream valleys in the northern half of the basin are aligned with the major and minor faulting which created the Basin and Range.

Chronologically, the oldest stratigraphic member within the basin is a Tertiary tuffaceous sequence of lower Miocene age, which is roughly contemporaneous with the John Day Formation to the north and east of the basin. The tuff has rhyodacitic airfall and flow members although some portions are noted to be welded (Walker 1963). This member covers a substantial portion of the surface of the basin. This, along with Taf, a tuff-breccia and tuffaceous sediments, are designated as part of the Cedarville Series in California listed as "Tmc: massive tuff-breccia, basalt and andesite" by the California Department of Water Resources (CDWR) (1982) (See Figure 3).

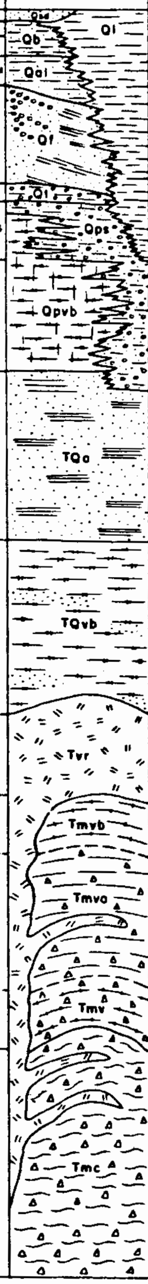
Moving up-column, upper Miocene volcanics include basalt, andesite, and pyroclastic flows (Tv) and the ubiquitous Tertiary basalt (Tb) associated in time with the larger lava outpourings of the Columbia River Plateau. Early (Lower) Pleistocene volcanics are quite similar to those preceeding (vesicular flows of olivine basalt and basaltic andesite,) but are less commonly distributed within the basin. Faulting is most prominent in these Early through Late Miocene formations and diminishes, as does the amount of volcanism, across the Miocene-Pliocene boundary.

The Lower Pliocene marks a change in the type of volcanism from effusive basaltic eruptions to more viscous rhyolitic to dacitic intrusives (QTra, QTd) and extrusives also of a more silicic character. Scoria, agglomerate, rhyodacitic and pyroclastic flows typify this transition, and formations denoted by QTv or QTvf show their stratovolcanic form in the western and northwestern parts of the basin. These formations are classified as "highly jointed lava flows of basalt with zones of scoria and sediments" on the California side (CDWR 1982).

Some Pliocene to Pleistocene volcanics end the volcanic sequence. Mostly basalt, these rocks are also highly jointed. At the Pliocene-Pleistocene boundary another

GEOLOGIC FORMATIONS IN GOOSE LAKE VALLEY

GEOLOGIC AGE			GEOLOGIC FORMATION	APPROXIMATE THICKNESS IN FEET
CENOZOIC	QUATERNARY	RECENT	SAND DUNES	0-6
			LAKE DEPOSITS	0-1000
			BASIN DEPOSITS	0-100
			INTERMEDIATE ALLUVIUM	0-100
			ALLUVIAL FANS	0-300
		PLEISTOCENE	TERRACES	0-50
			NEAR-SHORE DEPOSITS	0-250
			PLEISTOCENE BASALT	50-200
	TERTIARY	PLIOCENE TO PLEISTOCENE	ALTURAS FORMATION	500
			PLIO-PLEISTOCENE BASALT	500
		MIOCENE TO PLIOCENE	RHYOLITE	?
		MIOCENE	BASALT	?
			ANDESITE	
			BASALT, ANDESITE, AND TUFF	
			CEDARVILLE SERIES	7500



PHYSICAL CHARACTERISTICS	WATER-BEARING CHARACTERISTICS
Qsd: Unconsolidated fine sand, wind deposited.	Contains little water.
Ql: Unconsolidated clay and silty clay, alkali present.	May yield small amounts of poor quality water.
Qb: Unconsolidated, interstratified clay, silt, and sand. May have alkali.	Permeability moderate to slight. Yields small supplies of water to shallow wells.
Qal: Unconsolidated, poorly sorted silt and sand with lenses of gravel.	Moderate permeability. Yields moderate quantities of water to wells.
Qf: Unconsolidated to poorly consolidated, poorly stratified sands, gravels, and silts with lenses of clay.	East side fans are moderately to highly permeable and may yield moderate to large amounts of ground water to wells. West side fans are of relatively low permeability and may yield only small amounts of ground water to wells.
Qt: Unconsolidated, poorly sorted gravels and sands with interstitial clay.	Moderate permeability. Yields moderate quantities of water to shallow wells.
Qps: Slightly consolidated and cemented, poorly to well stratified pebbles and cobbles with lenses of sand and silt.	Moderate to high permeability. May yield large quantities of water to wells. Contains some confined water.
Qpvb: Highly jointed, flat-lying olivine basalt flows with interbedded scoriaceous zones.	Unit as a whole is highly permeable. Acts as a forebay to water-bearing sediments in Goose Lake Valley. May yield large quantities of water to wells.
TQa: Slightly consolidated, well bedded tuffaceous sandstone.	Moderate permeability. May provide moderate quantities of water to deep wells, may contain confined water.
TQvb: Highly jointed lava flows of basalt with zones of scoria and sediments.	Highly permeable on the whole. Acts as forebay to water-bearing sediments in Goose Lake basin. May yield large quantities of water to wells.
Tvr: Light-colored rhyolite, with zones of obsidian.	Essentially impermeable.
Tmvb, Tmva, Tmv: Jointed lava flows of basalt and andesite, intrusive plugs of andesite, beds of tuff and tuff-breccia.	Nearly impermeable. May yield small amounts of water from fractures.
Tmc: Massive tuff-breccia, basalt and andesite.	Nearly impermeable. May yield small amounts of water from fractures and joints.

Figure 3. Stratigraphic column for Goose Lake Valley (California Department of Water Resources, 1982).

significant stratigraphic change occurs. The phase of effusive and explosive volcanism (constructive) ends and a more erosive cycle begins, as witnessed by an increasing proportion of volcaniclastic sediments in the stratigraphic column. The predominant sedimentary formation produced as a result of this marked change is classified as QTs (Oregon) and Qf, Qps, Ql (California). The sedimentary rock types associated with this period are mostly fluviatile, composed of mostly consolidated to unconsolidated sands, gravels, and silts in alluvial fans, with the remainder being lacustrine or aeolian. Some water-lain volcanic flows are found in these sediments, although volcanism was waning (Walker 1963).

The Pleistocene-Holocene period witnessed a cessation of volcanism (at the boundary) with an increase in the amount of lacustrine sediments (Ql) relative to alluvial sediments (Qal). This period marks a transition from an aggressive erosional period to the present depositional (constructional) period. It is conceivable that at this time a lava flow blocked-off the outlet to the basin and is responsible for the ponding which occurred. Lacustrine deposits dominate the recent record even though some sand dunes formed in more recent times in nearby closed basins.

This drier, more recent period is essential for the exposure and consolidation of playa deposits (Qp) along Summer Lake and Lake Abert to the north and Surprise Valley to the east, but did not produce any such deposits along

Goose Lake. This is strong evidence that the comparatively anomalous freshwater environment of Goose Lake has been a long-standing feature unique among the regional closed-basin lakes.

In summary, the geologic history of Goose lake is dominated by a long period of explosive and effusive volcanism which has been characteristic of the basin and range since the Lower Miocene, producing extensive basalt flows, pyroclastic flows, and tuffs. The tectonics of the period also produced regional faulting along a north-northwest to south-southeasterly orientation dissecting the Miocene rocks. Basalt and andesite flows mark the end of the Cenozoic, ushering in a new tectonic regime suitable to the formation of stratovolcanoes. The Quaternary was a period of decreasing volcanism relative to erosion with the extensive formation of alluvial fans and lacustrine deposits. Interpretation of the column reveals that Goose Lake was dammed in the Early Pleistocene by lava flows at the southern end of the basin due to the relative age of the flow and the more recent age of the sediments, previously limited in extent.

Climatologic Setting

Development of a reliable water budget model for Goose lake requires accurate climatologic data since the major input, precipitation, and the only identified loss, evaporation, are truly the elements which drive the model. Climatologic data pertinent to this study are based on records from Lakeview, Oregon, located less than ten miles from the lake and covering the period 1884 to the present.

The general climate of the basin is transitional between the moist cool winter and dry warm summer of the Cascade Mountains on the western edge of the basin to the moderately wet cold winter and hot dry summer of the Great Basin. Winter weather is controlled by cold frontal systems which move from west to east, and bring the majority of the annual precipitation. Cold continental air from the northeast keeps the mean air temperature lower than at points west. The average elevation of the basin (between 5000 and 6000 feet) also enhances colder winter temperatures.

Summer weather is alternately dominated by the warm dry air of the North Pacific High and by moister unstable air which invades the Great Basin from the south, causing convectional precipitation. This annual variation produces a relatively moist and cold winter during which most of the annual precipitation falls. The summer is generally quite warm and dry, but of short duration, with sporadic convectional precipitation.

Temperature records have been kept at Lakeview for many of the years since the establishment of the station in the 1880's (National Weather Service, miscellaneous years). Available records are incomplete prior to 1928. Because of this the more recent period has been used for source climatic data.

Examination of the 1946-1975 weather record at Lakeview reveals a mean annual temperature of 46.8°F. The warmest month is July (67°F) and the coldest month is January (29°F), based on average monthly temperatures. The greatest range of monthly temperature extremes occurs during the summer months where a typical spread of more than 30°F is found. During the winter the mean monthly temperature minima and maxima may vary by only 15°F (Figure 4).

The length of the growing season could be determined as the period during which the minimum temperature is above freezing. According to the Lakeview record, this would extend from the middle of April until the the middle of October. The length of the growing season is therefore estimated to be six months long.

Seasonality of precipitation is shown in Figure 4 for Lakeview. Precipitation increases from an average low of 0.27 inches for the month of July to the average high of 2.29 inches in January with the average total for the 1946-1975 period being 15.74 inches. A secondary peak occurs in May after which precipitation steadily decreases. If the water year is divided into two six month periods, October through March best represents the wet season during which 67 percent of the total precipitation falls.

As the majority of preciptation falls within the colder

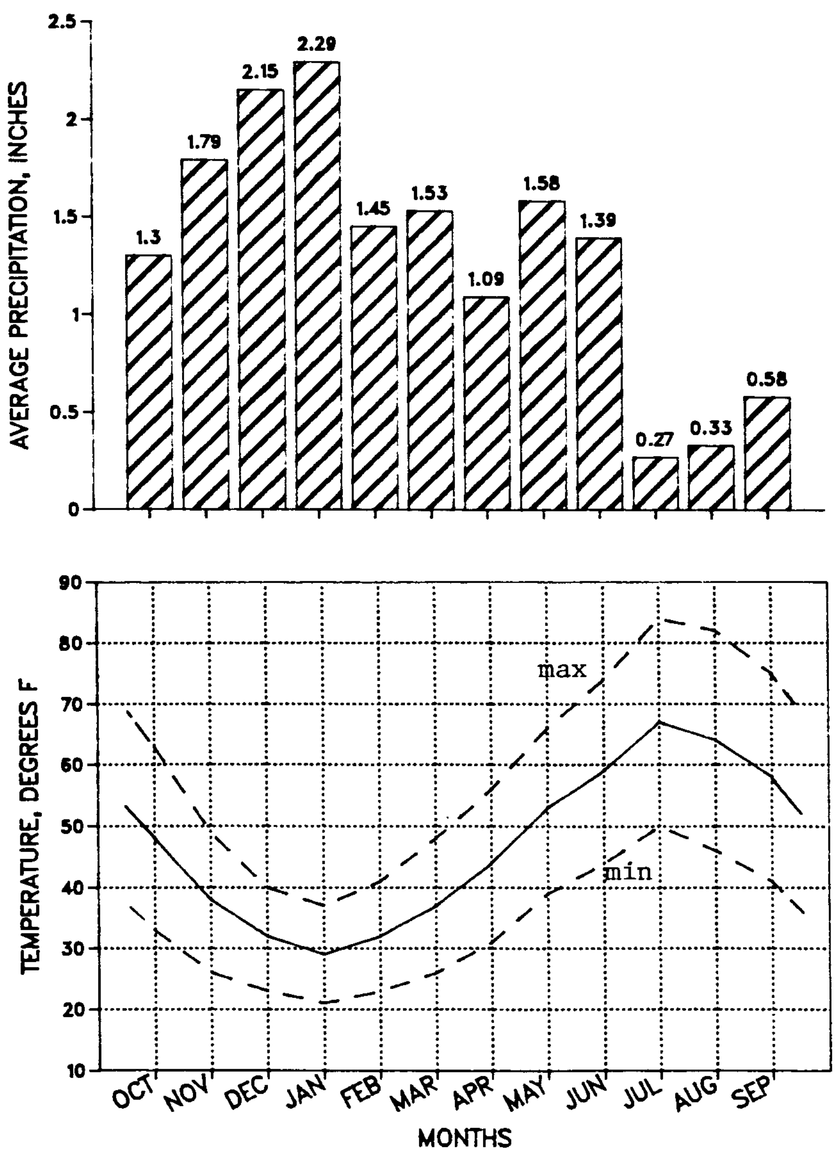


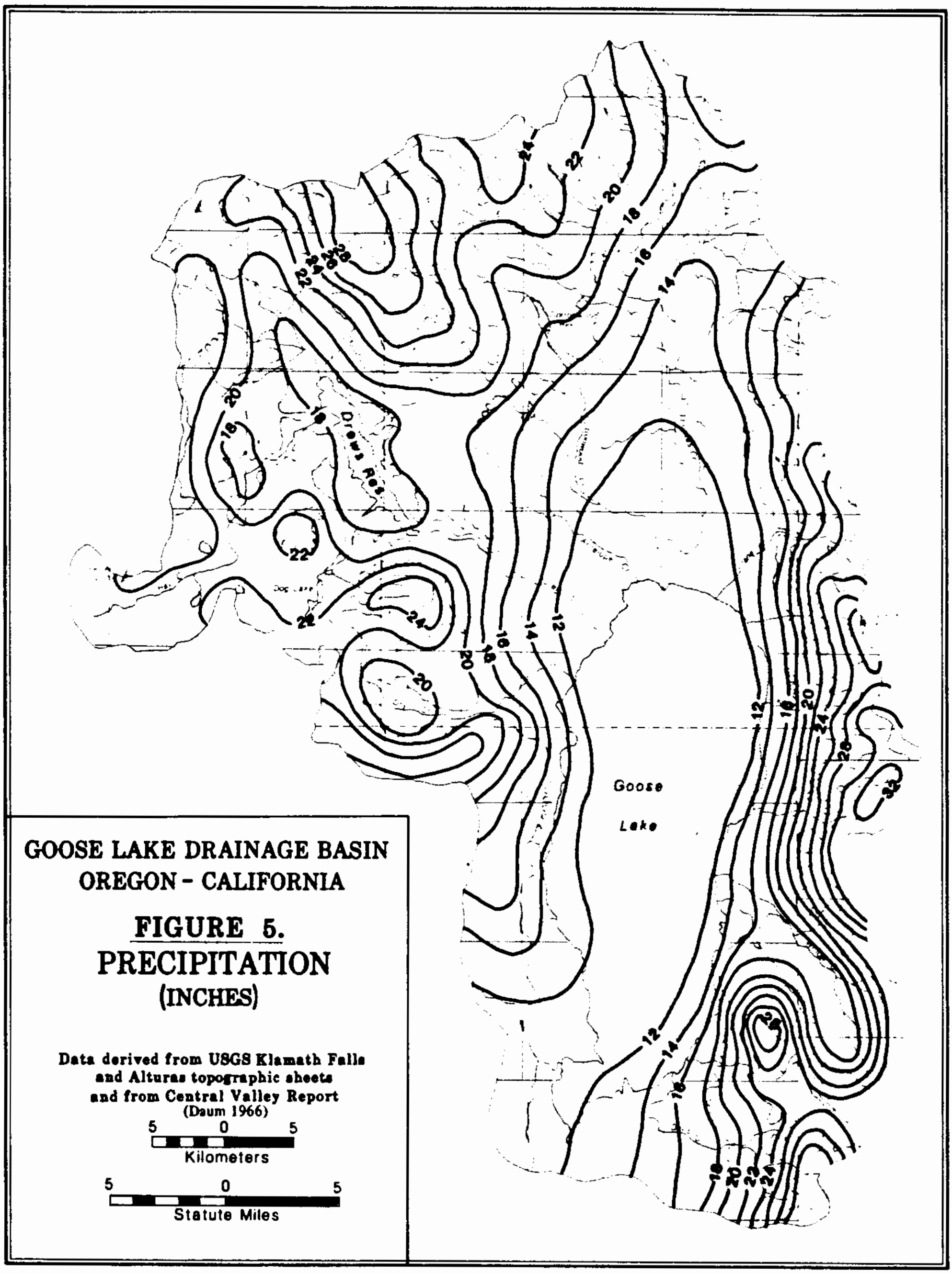
Figure 4. Precipitation and temperature profiles by month at Lakeview, Oregon (National Weather Service, 1946-1975).

months, a major component of the basin precipitation is snowfall. Although the annual water budget model will not distinguish between types of precipitation in an annual total, a background on snow data is presented here. Snowfall is monitored by the USDA Soil Conservation Service at several locations within the Oregon portion of the basin while the California Department of Water Resources maintains snow courses in California. Two stations, Quartz Mountain and Strawberry Butte are equipped with telemetry to relay water equivalent of daily snowpack to SCS receiving stations in Idaho and Colorado. Several other snow courses are periodically visited for prediction and calibration of data to forecast runoff from snowmelt.

Extension of annual precipitation averages from measured locations to locations throughout the drainage basin by way of an isohyetal map was undertaken by the California Department of Water Resources (CDWR 1963), shown in Figure 5. A strong topographic control over the spatial distribution of precipitation can be seen. This map is the only detailed analysis of the spatial distribution of precipitation available for the basin.

Hydrologic Setting

Goose Lake basin, situated between the Great Basin where intermittent streams are common, and the Cascades, where streams are usually perennial, shares characteristics



GOOSE LAKE DRAINAGE BASIN
OREGON - CALIFORNIA

FIGURE 5.
PRECIPITATION
(INCHES)

Data derived from USGS Klamath Falls and Alturas topographic sheets and from Central Valley Report (Daum 1966) of both areas. Streams which drain the Fremont Mountains to the west have densely forested watersheds and go dry less frequently than streams on the eastern edge of the basin which drain across alluvial fans to the lake, as in Figure 1. The figure contains only names for the major stream subbasins.

Fifteen streams in the basin have been gaged for some period of time by state and federal agencies. A list of stations is given in Table I. Drainage characteristics are also given for the streams in addition to basin elevation, mean flow, and discharge area. Despite the variable record length, mean annual discharge volume correlates well with drainage area above each gaging station. A least-squares analysis reveals a highly significant correlation between drainage area and annual discharge. The correlation coefficient is 0.96, indicating that drainage area explains 92 percent of the variance in mean annual discharge. The equation:

(1) $$Q_{AF} = 230.8A + 2108$$

where Q_{AF} = Acre-feet annual yield

A = Area in square miles

approximates this well-defined relationship.

Only two streams have what could be called a long-term record -- Drews and Cottonwood Creeks. The annual runoff

TABLE I

DRAINAGE AREA CHARACTERISTICS FOR
STREAMS IN GOOSE LAKE BASIN

Station Name	Area (mi^2)	Years Record	Mean Elev. (ft)	Ann. Flow (AF)	Flow/ mi^2	Data Source
Oregon stations						
Augur Cr.	10	4	6100	2060	206	OWRD
Bauers Cr.	65	6	5300	13,260	204	OWRD
Camp Cr.	30	4	5900	4000	133	OWRD
Cox Cr.	20	6	5500	7200	360	OWRD
Crane Cr.	13	1	5800	3480	267	OWRD
Cottonwood Cr	33	60	5100	15,290	463	USGS
Drews Cr.	212	50	5000	51,150	241	USGS
Dry Cr.	25	6	5000	8700	348	OWRD
Kelley Cr.	7	2	5800	1700	242	OWRD
Thomas Cr.	28	12	5600	14,500	517	OWRD
California stations						
Cottonwood Cr.	9	10	5800	1800	200	CDWR
Davis Cr.	24	13	6000	8100	338	CDWR
Lassen Cr.	27	16	5800	13,000	481	CDWR
New Pine Cr.	20	15	5300	8800	440	CDWR
Willow Cr.	35	5	5300	7400	211	CDWR

Sources: USGS-Water Resources Division, miscellaneous data
OWRD, 1978
California Dept. of Water Resources, miscellaneous data.

from Cottonwood Creek shows less of the effects of diversion than Drews Creek, upon which a large reservoir and diversion works are located. Cottonwood Creek was thereby chosen as the most representative stream for analysis of discharge trends.

A statistical summary of streamflow characteristics recently published by Friday and Miller of the USGS (1984) shows mean, minimum, and maximum monthly discharge in addition to exceedance probability tables for Cottonwood Creek for the period 1914 to 1981. Figure 6 shows the typical discharge values from the USGS report. The discharge relative maximum during February follows the precipitation maximum during January. The true maximum discharge during May represents both a rainfall peak during May and snowmelt runoff from the winter snowpack. The minimum discharge tends to occur at the end of the water year, one or two months behind the precipitation minimum.

The mean discharge (solid line) shows that flow is usually present, although not in great quantity. The drainage area above the gaging station is forested and very little diversion occurs but some retention at Cottonwood Reservoir ensures a flow during the late growing season. No storage is maintained beyond September so the annual (water year) flow to Goose Lake is essentially the same as if unregulated, minus minimal evaporative loss from the small reservoir.

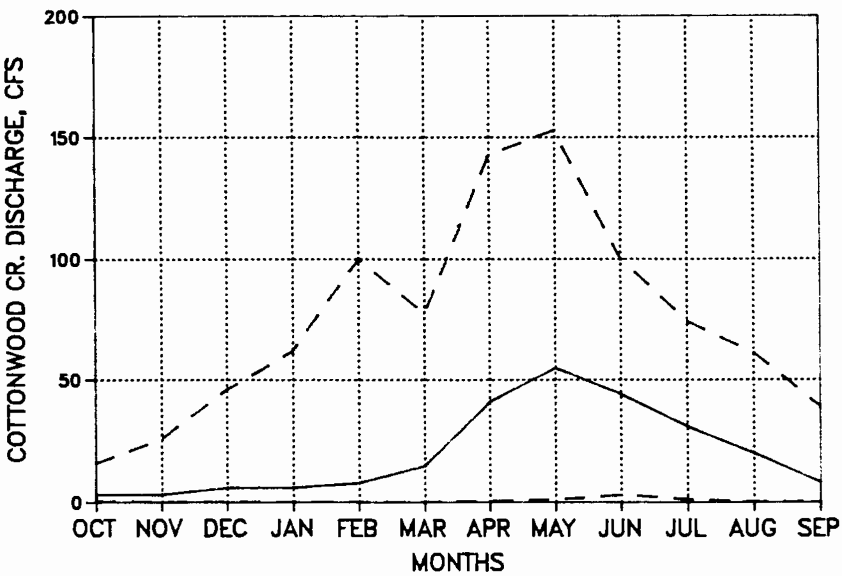


Figure 6. Average monthly discharge for Cottonwood Creek, Oregon 1914 to 1981 (Friday and Miller, 1984).

Although eleven partial record gaging stations exist in the basin, only 500 square miles are represented by drainage area upstream of the gages. Given that the total drainage area is 1100 square miles and the surface area of the lake and shoreline covers an additional 200 square miles, 400 square miles are unaccounted for. The annual runoff from this ungaged area, predominantly lowlands and smaller drainages, is difficult to derive given the diverse nature of the gaged drainage area. The reconstruction of total annual basin runoff will therefore rely upon a coefficient (1.8) applied to gaged runoff to represent total runoff in the basin.

Modification of Streamflow

Two significant reservoirs (on Drews and Cottonwood Creeks) exist in the basin to serve downstream irrigation demands. Drews Reservoir has a diversion works which distributes a portion of its flow to lowland farmland via irrigation canals. Cottonwood Reservoir releases water into the natural watercourse for downstream use during lower flow periods.

Diversion for irrigation is the most prominent use of surface water in the basin. In 1955 in California, 11,000 acres of land were irrigated (California Department of Water Resources 1982). In Oregon during the same period 11,400 acres were irrigated (Daum 1966) mostly from surface water sources. In the late 1970s, 10,300 acres of California (California Department of Water Resources 1982) and 38,820 acres of Oregon (U.S. SCS 1978) were being irrigated with mostly surface water in Oregon and groundwater in California. Water-intensive crops such as alfalfa are more commonly raised now and water requirements have increased accordingly. Estimated crop demand for both sides of the basin using the weighted net irrigation requirement of 1.24 feet per acre would be 68,800 acre-feet per year, given present acreage.

Most irrigation withdrawal occurs downstream of the stream-gaging sites and therefore is not accounted for in reported streamflow. This is somewhat balanced by ungaged streams -- a coefficient which could be adjusted accordingly. In addition, irrigation water is usually applied by flood or sprinkler methods leading to overland return flow to the stream, ditch, or lake. Without performing a more detailed study on basin irrigation water use, the net effect of withdrawal is unknown, but may explain a trending deficit or surplus seen later in the modelled annual water budget series. One estimate would be to use the estimated crop demand, above, of about 30,000 acre-feet in the mid-1950s to about 70,000 acre-feet in the late-1970s with considerable inter-annual variation. This correction trend may be applied during calibration of the model.

Groundwater withdrawal in the California part of the basin has been increasing as surface waters are becoming more fully appropriated. Wells show a groundwater decline of up to 13 feet in a portion of the Davis Creek subbasin which may point to a local overdraughting of the alluvial aquifer (CDWR 1982). The extent of the resource and its withdrawal are a current focus of study by the California Department of Water Resources. No study has been scheduled for the Oregon part of the basin.

CHAPTER III

LITERATURE REVIEW

History of Lake-Level Fluctuation Research

The recognition of the dependent relationship between closed-basin lake level fluctuation and long-term climatic change was identified by Gilbert in 1880. Several of his published surveys of the intermontane states detailed the history of the fluctuation of Lake Bonneville, the Pleistocene predecessor of the Great Salt Lake. Relying primarily upon stratigraphic evidence (as his reconnaissance was concerned at first with the geologic history of the basins) he reconstructed a series of former lake levels, the highest of which lies 1000 feet above the current lake surface (Gilbert 1880).

Gilbert advanced the theory that the pluvial lakes of the past were contemporaneous with the advances of the glaciers during what he terms the "Ice Epoch." Noting the appearance of the thickest lacustrine deposits interbedded between the older and younger alluvial deposits, Gilbert believed that the Bonneville period was clearly moister than either the current or preceeding periods, and that it did in fact coincide with glacial advances from the Wasatch Range.

A similar reconstruction of events during the Pleistocene was also conducted by Russell on pluvial Lake Lahontan, located in northwestern Nevada. Like Gilbert, Russell observed a periodicity in the pluvial record, but in this case from examination of carbonate deposits known as "tufa" (Russell 1883). Russell's chronology appears to parallel that proposed by Gilbert, in that it described two earlier periods anomalously wetter and cooler than at present with an intervening drier period.

Since the 1880's many researchers have investigated the histories of Lakes Bonneville and Lahontan, among other Great Basin pluvial lakes, and have more accurately identified the chronology of events there. Using radiocarbon dating of buried organic material, pollen concentrations, and other stratigraphic aids, workers such as Jennings (1957), Morrison (1965), and Scott (1980) have refined the dating of pluvial deposits to within hundreds of years, but are still describing general lake level oscillations with frequencies of many hundreds to thousands of years.

Of great importance to lake-level fluctuation studies are the behavior of climatic and hydrologic elements over short periods of time, manifest by their cumulative nature in lake level response. By examining short-term climatic changes (less than a decade) and the associated hydrologic response, the lake-level record should clearly depict shortages and surpluses in available water supply not readily interpreted from precipitation series data alone.

Contemporary lake-level studies in this century could be summarized as (1) calibrating precipitation-runoff records against lake inflow data, (2) the response of lakes directly to current and reconstructed climatic conditions, and (3) the use of lake level change as an index of available water supply. On the whole, studies of closed-basin lake-level fluctuation are extremely rare in the literature due to the sparcity of annual lake-level records for a period long or continuous enough to perform reliable water balance computations.

Hardman and Venstrom (1941) investigated the fluctuation of Pyramid and Winnemucca Lakes, Nevada, from 1850 to 1940. The focus of their study was to develop a 100-year runoff record for the Truckee River at its terminal confluence with the lakes. The study was motivated out of a concern over rapidly declining lake levels during the years immediately preceeding the study. Indian treaties required the knowledge of the mean annual runoff for the river and its historical contribution to the lakes.

A discontinuous lake-level record was augmented with continuous runoff records for the Truckee from 1900 to 1939.

Precipitation records from the west and east slopes of the Sierra Nevada were used to prepare an index from which older streamflow records could be reconstructed. Periodic streamflow measurements on the Truckee prior to 1900 increased the confidence of the reconstruction of annual runoff for the period. Finally, streamflow minus diversions were used to calculate inflow into the two lakes.

Conclusions from their study show that (1) drought was common in the basin prior to 1840, (2) a generally wetter period was experienced from 1860 to 1917, (3) a drought of similar intensity to that of the 1920's-1930's occurred during the 1840's, and (4) the period between 1840 and 1917 was anomalously moist.

To prepare annual runoff means, actual annual lake levels were not required; only decade approximations and some known or inferred levels are given. The relationship between the recent levels (circa 1940) and those of the preceeding 90 years are only compared on relative terms. Had actual lake levels been recorded for a portion of the record, an additional correlation tool could have been used in runoff calculations.

Lawrence and Lawrence (1961) investigated the apparently concurrent nature of glacial advances and brimming closed-basin lakes. They examined twenty lakes in the western United States to determine the similarity between pluvial and glacial response to short-term climatic change. General lake response to climate was fairly consistent among the lakes, with high water noted at the turn of the century. Lake recession was noted between 1920 and the mid-1930's. Regional glacial advances during the 1950's appear to coincide with the maxima in lake stages, as had been previously identified. Unfortunately, no attempt was made to demonstrate via mass balance equations the validity of this synchronous behavior, suggesting little more than was previously known.

Harding (1965) was the first to investigate the contemporary fluctuation of lakes in a more scientific manner. His goal was to extend streamflow and precipitation records into the past to evaluate more reliably the variability of water supply over the last few hundred years as a pattern for the future. Harding's reconstruction of past conditions relied upon historical observations, precipitation, streamflow, and tree-ring records.

Harding initially compared annual precipitation to runoff for the Lake Tahoe basin. As with most basins in the intermontane region (including the Goose Lake Basin), correlations between annual precipitation and runoff totals are typically poor, even if precipitation is lagged to account for the previous year. Harding also recognized the utility of tree-ring widths in preserving a record of water availability similar to that shown by streamflow, although his concern over inconsistencies between ring data collected by separate researchers prevented his extension of runoff data through use of the tree-ring records.

A reconstruction of probable lake level for Goose Lake is given by Harding as a composite of historical observations from 1832 to 1960. His main purpose was to evaluate whether the water supply deficiency of the 1840's was more severe than that of the 1920's-30's. Examination of both periods showed that the latter shortage was more severe than the former, although graphically, a plot of cumulative departures from mean runoff indicate that the net deficit was both greater and more prolonged in the 1840's-50's than during the 1930's (Figure 7). This apparent inconsistency is not explained in the text.

The presence of 75 year-old tree stumps and worked obsidian chips on the bed of Goose Lake when it was nearly dry in 1926, as documented by Harding, indicates that periods of prolonged drought prior to 1830 were recurrent and as extreme as in recent times. Harding does evaluate research done by Antevs (1938), Davis and Sampson (1936), and Keen (1937) on tree ring width data collected in the Goose Lake area with a common record of 450 years. Noting a pronounced lack of consistency between tree-ring records within a fairly small region, Harding discounts the use of

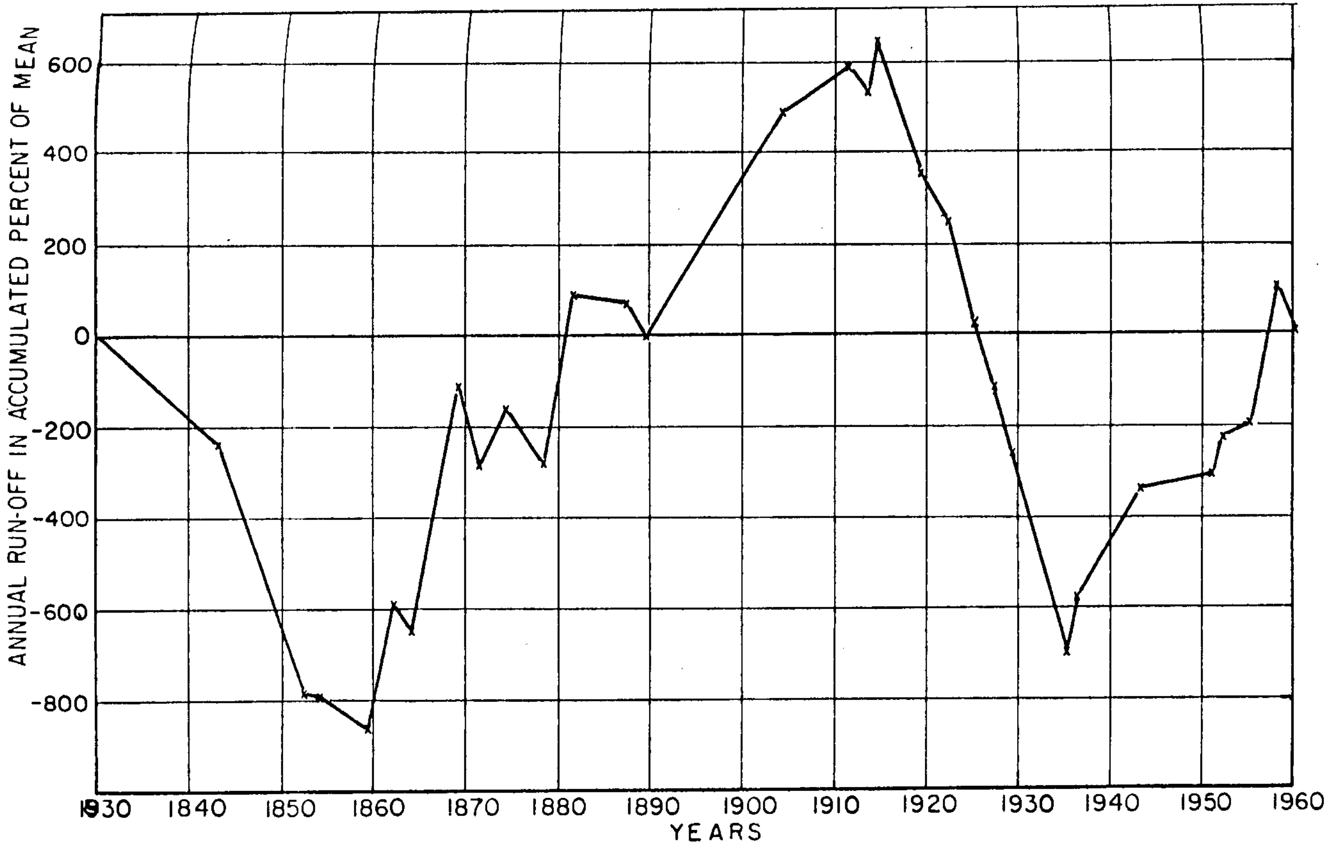


Figure 7. Accumulated departure from the mean of runoff, Goose Lake drainage basin, 1830 to 1960 (Harding 1965).

tree rings as reliable indicators of specific hydrologic or climatic conditions.

Use of Tree-rings in the Reconstruction of Hydrologic Time Series

The major problems confronting investigators interested in developing a high resolution chronology of glacial or pluvial events are the limited number of reliable dating techniques and the paucity of undisturbed or consistently dateable material. The annual growth rings of trees is a remarkably good indicator of moisture availability at a site and is usually a composite function of precipitation, growing season length, and soil moisture. Tree rings have been used to reconstruct both precipitation and runoff series, and will therefore be very useful in reconstructing lake level series.

Hardman and Reil (1936) were among the first to use tree-ring records to reconstruct annual streamflow records. These authors demonstrated that a high correlation existed between tree-ring indices and the runoff of the Truckee River. The direct comparison between the data did not yield a very high correlation coefficient, however. The use of a five-year running mean on precipitation data acted to smooth out the series such that correlation coefficients as high as 0.89 were achieved. Although the authors justify using the moving average as a physically-based component of soil moisture, the present year's soil moisture is not a result of both the next two and the last two years. This choice of a smoothing technique would appear to be less applicable than one which represents precipitation as a product of current and preceeding values only. The smoothing of both series might be forcing a similarity which in nature has a more complex basis.

Keen (1937) evaluated the relationship between tree-rings and precipitation in eastern Oregon and went on to compare each to annual runoff patterns of the Columbia River at the Dalles. Keen plotted the percentage departure from the mean for all three series and derived an unsmoothed correlation coefficient of 0.56 between runoff and tree ring indices for more than 50 years of data. This is reasonably good considering the distance between the river and tree ring sites. Keen achieved a correlation coefficient of 0.82 by comparing annual ring width departure from the mean against a 2-year cumulative departure of precipitation. This comparison appears to demonstrate the lagged soil moisture response to precipitation. A similar lag procedure was not attempted on runoff data.

Keen did demonstrate a high consistency between local and regional tree-ring growth, a result of careful selection of sites not altered by fire or other disturbance. This choice of ring sites undoubtedly led to his high correlations with precipitation and runoff. Fritts (1969) suggests that trees located in the driest sites tend to optimize the climatic 'signal' and minimize the other environmental 'noise' encountered.

Stockton, currently a professor with the Laboratory of Tree-Ring Research at the University of Arizona completed his doctoral dissertation on the "Feasibility of Augmenting Hydrologic Records Using Tree-ring Data" in 1971. The major findings were recompiled into Paper Number 5 of the Laboratory (Stockton 1975). This document is the most comprehensive study prepared to date on the use of tree-ring data in runoff series reconstruction. Two sub-basins in Arizona and New Mexico were selected for study -- one small (101 mi^2) and characterized by a snowmelt runoff peak, and one larger (1653 mi^2) which has a winter runoff derived from both snowmelt and rainfall. The objective of Stockton's investigation was to determine the variability of (1) runoff response to climatic elements and (2) tree-ring response to climate (Stockton 1975, p. 12).

Stockton used principal component analysis to characterize the variability in both precipitation and runoff series on a monthly basis for both drainages. The correlograms of monthly precipitation and runoff show greater periodic correlation for each in the smaller watershed. The larger watershed exhibits a possible groundwater lag component and/or shows a composite response to climate which yields a lower correlation between monthly precipitation and runoff.

Stockton's examination of the tree-ring series showed that few discernable trends could be seen among sites within the two study areas, although inter-site correlation was quite high, with r^2 approaching 0.80. Sites with greater sensitivity were noted by Stockton as those on south- and east-facing slopes "...where temperatures are higher and consequently evaporation and transpiration rates are greater" (Stockton 1975, p.46).

Stockton and other authors have identified the physical factors which lead to a similar response to climate by both hydrologic and tree-ring series. Logically, annual runoff may be characterized by the idealized equation (Stockton 1975, p. 53):

$$Q = f(r - E \pm \Delta s) \quad (2)$$

where
Q = total annual runoff
r = total annual precipitation
E = evaporation + transpiration
$\pm\Delta s$ = change in soil moisture storage.

Stockton attempted to develop a physiological response function for tree ring growth utilizing both heat and water balance equations, but in its complexity only low correlation statistics were derived. The elements, annual precipitation, annual runoff, and available energy are plausible components in ring width growth, but together were not easily modelled.

Again using eigenvector analysis to derive the amplitude of monthly precipitation and temperature variability, Stockton determined that the water year series of climatic variables does parallel the physiological response of the trees better than the calendar year series.

Evaluation of the runoff series via principal component analysis appeared to account for a large portion of the variance encountered among the data collection sites, but the comparison of gaged versus reconstructed flow yielded a correlation coefficient of only 0.512 for the smaller watershed. Results of correlation analysis are not given for the model response in the larger basin.

Given that the correlation between the principal components model output approximated that reported by other authors (such as Keen, 1937) it appears that the methodology offered by Stockton is little better in its application than less intensive regression analysis. Stockton defends his approach by demonstrating the eigenvector technique on the Colorado River at Lees Ferry, Arizona against many tree ring sites in the headwater region. Not too surprisingly, a very high correlation (r=0.91) was derived for this extremely large basin where error in flow was on the order of millions of acre feet per year and extremes in flow are dampened by the diverse nature of its tributaries. Nevertheless, Stockton has shown that variability among many like data sets may be well characterized by principal component analysis.

More closely related to the topic of this thesis, Stockton and Fritts (1973) developed a straight correlation model between lake levels and tree ring widths of lakeside trees. The construction of a dam on an tributary to Lake Athabasca, Alberta, initiated a decline in lake level, potentially threatening the lake ecology. Authorities became interested in knowing the historical record of lake level fluctuation, but had only partial elevation records for a short time period. The known period (33 years) was used as a calibration period during which lake levels in sloughs surrounding the lake were correlated with tree-ring growth as a linear function.

Stockton and Fritts used ring width indices as direct evidence of water level changes without using the precipitation or runoff components common to previous studies. This was justified by the fact that the trees sampled were in a lowland area with a shallow water table which communicated directly with the lake surface. Results of the reconstruction show that the existing level records were fairly close to the long-term mean and that the most recent period (1941-1960) lake levels were far lower and showed a lesser variance than the reconstructed record (1810-1967). This latter period corresponded to a drier period interpreted from both precipitation and runoff data. Independent accounts of relative lake elevations supported the reconstructed series.

For the study at Goose Lake, the use of tree rings to infer lake level, such as was done with Lake Athabasca, does not appear to be a reasonable (physically-based) response as sampling sites chosen for this study were in moisture-sensitive (xeric) zones far above the lake. Ponderosa pine, selected for ring-width sampling at the Goose Lake site, possess a tap root which accesses the shallow water table. The water table sensitivity of the trees, however, should reflect a lagged response to seasonal precipitation, and should relate more to groundwater than to the distant lake surface.

Returning to research relating tree-rings to runoff, Holmes, et al. (1979) compiled a tree ring chronology in the Argentine Andes to compare to the annual runoff series of the Neuquen and Limay Rivers. Using least squares analysis, the tree-ring values were lagged to approximate the hydrologic series. Comparison between the observed and reconstructed runoff showed a correlation coefficient of 0.73. This study shows that given reliable tree-ring series collected in climatically and hydrologically sensitive areas (preferably in the headwater region), a significant annual correlation can be drawn between streamflow and tree-ring data.

Cook and Jacoby (1983) developed a model to extend summer "low-flow" runoff records for the Potomac River using tree-ring width indices. Monthly streamflow values were compared to tree-rings by way of canonical regression analysis -- a means of predicting multiple dependent variables from multiple predictors. They warn that one should limit the number of predictors to avoid high r^2 statistics derived from colinearity rather than dependence. By establishing a threshhold significance level ($p<0.05$), many potential predictors with a less significant dependence were eliminated, leaving only the most highly correlated parameters.

The authors then established calibration and verification periods to further test the various equations derived for each month. Two tests were employed to evaluate the accuracy of the reconstruction -- the product-moment correlation coefficient (r) and the reduction of error statistic (RE) -- the latter of which showed a high sensitivity to error for the process attributed to only two anomalous years with an intervening dry year (Ibid., p.1666). The product-moment correlations for the seasonal composite ranged from 0.541 to 0.767 for the verification periods, significant at the 95% level (Ibid., p.1670). Interpretation of their results showed that the severity of the low-flow period encountered on the east coast during the 1960's was unrivaled since 1730. This knowledge is helpful to water resource planners interested in knowing the variability of the potential water supply for the Washington, D.C. area.

Cook and Jacoby have also shown that tree-ring data may correlate well with summer low-flow values, and contend that such a relationship is physically-based since deciduous trees in a humid environment accumulate most of their carbohydrate stores during the summer. This property of tree-rings would appear to have great potential in determining the recurrence interval and severity of low-flow events to meet the data requirements of recent "minimum streamflow" legislation passed in several states.

Other applications come from as far afield as studying the feasibility of streamflow record extension by tree-rings in Tasmania (Campbell 1980) to a study currently being undertaken by the U.S.G.S. in Nevada (personal communication, C. W. Stockton 1984) where different species of trees sensitive to different climatic elements are being used to develop a precipitation-runoff record for water supply analysis of several closed-basins. If past successes are any indication of future promise, more applications will be conceived and supported in the not too distant future as reconstructed records become more essential to water resources management.

CHAPTER IV

METHODOLOGY

The approach to the derivation of a lake-level fluctuation model is divided into two related parts, both of which require extensive explanation and testing. The first portion is the development of a model to determine year-end lake-levels or volumes. This development is a necessary precursor to the second portion of the thesis -- the reconstruction of lake volumes or levels on the basis of tree-ring data -- covered in Chapter V.

Model Development

The method used in modelling lake level fluctuation at Goose Lake was constrained by the availability of data and the nature of the desired product -- a year-end lake volume or surface elevation. The most critical component, actual lake-level observations, is also the most rare. Very few lake level records exist prior to 1946 or since 1975, but during the intervening period, frequent measurements were made. During the late 1950's and early 1960's several observations per month were common whereas toward the ends of the study period, only one or two levels were recorded per year. For this reason the initial study period used for model calibration was 1946 to 1975. Streamflow, precipitation, temperature, evaporation, and lake-level records exist for the basin, although some records cover only a portion of the 30 year study period. Extension of these elements by statistical means recreated the full coverage with a reasonable accuracy.

Estimation of lake volume for annual (water year) time increments was chosen over monthly estimation for many reasons. First, the availability of essential data varies with time such that monthly values were not reliably derived. Second, the effects of snowmelt and diversion on natural runoff vary from month to month, and year to year, leading to a similarly variable runoff response. This unpredictable effect is dampened almost totally if annual values are used. A comparison between annual precipitation and runoff for the Drews Creek subbasin yielded a correlation coefficient of 0.77, whereas monthly values decreased the coefficient to 0.50.

Third, and quite importantly, the use of tree-rings is constrained to annual increments which correspond roughly but conveniently to water years. The reconstruction of relative lake levels, described in the second half of this chapter will require annual rather than monthly values. Annual runoff, precipitation, and lake volume values also help to define recent long-term trends in data not readily seen in a monthly time series.

The most logical choice for a lake fluctuation model given the foregoing constraints is the water-budget method, or mass balance approach, documented by the U.S. Geological Survey (1954) and referenced by Dunne and Leopold (1978). This method was applied in a study at Lake Hefner, Oklahoma to calibrate evaporation estimation techniques. Optimum conditions cited by Dunne and Leopold for the application of this method are those "...where subsurface flows are essentially zero and surface outflow is small relative to evaporation" (Dunne and Leopold 1978, p. 100).

There is some question whether Goose Lake receives considerable groundwater contribution through its lakebed. Waring (1907) treated groundwater as a residual value in his estimated water balance of Goose Lake, claiming an average 288,000 acre-feet are added to the lake per year. Harding (1965) cited reports that springs were present on the lakebed when the lake was nearly dry in 1926. Phillips and VanDenburgh (1971) relied upon a longer history of precipitation, evaporation, and runoff observations in their analysis of Goose Lake. Their more rigorous conclusion was that the lakebed has not transmitted large amounts of groundwater to the lake. This opinion is further underscored by the relative magnitude of major additions to and losses from the lake compared to the amount of water which could be transmitted through the clay-rich lacustrine sediments. The sensitivity of the annual water budget is probably not great enough to document such a small contribution, should it exist.

In a time-dependent process within a closed basin, five major components can describe the hydrologic cycle expressed in lake volume. These are 1) antecedent and present lake volumes (V_{t-1} and V_t), 2) inflow volume from streams (I_s), 3) groundwater in/outflow (I_g and O_g), 4) direct precipitation upon the lake surface (P), and 5) evaporation from the lake surface (E_o). These elements create the following relation also diagrammed in Figure 8:

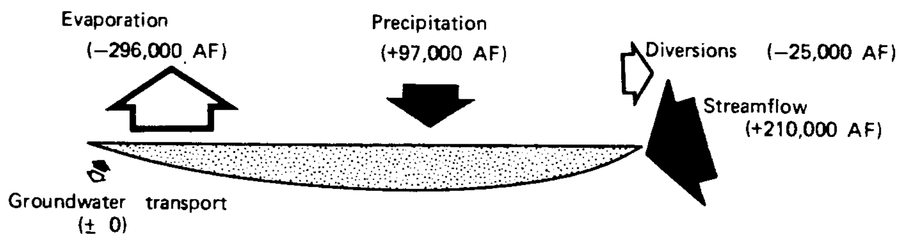
(3) $$V_t = V_{t-1} + I_s + P + I_g - O_g - E_o$$

The poorly documented natural system at Goose Lake requires that we include the groundwater components within our residual volume such that:

(4) $$V_t - I_g + O_g = V_{t-1} + I_s + P - E_o$$

$$\text{or} \quad V_t = V_{t-1} + I_s + P - E_o \quad \text{if } I_g + O_g = \emptyset$$

If groundwater withdrawal were to be significant and widespread relative to the surface inputs, it should be manifest in an increasing residual over time. Since groundwater does not contribute substantially to the maintenance of lake-level then the volume difference between observed (V_{tact}) and predicted (V_{tpred}) will vary with time according to other factors, yielding Equation 5.



$$\Delta s = P + S - D - E + G_{in} - G_{out}$$

Figure 8. Schematic diagram of lake gains and losses, Goose Lake, 1946 to 1975.

(5) estimation difference = $V_{t(pred)} - V_{t(act)}$

Once refined, predicted year-end volumes will be compared with actual volumes by way of regression analysis to determine the model's accuracy of prediction. Chapter V describes the reconstruction of hydrologic and climatic trends from 1422 to 1964 on the basis of tree-ring evidence.

Component Evaluation

The four main components to be quantified in this water-budget model are precipitation, evaporation, streamflow, and lake-level and volume observations. These will be discussed in the order given above presenting sources of primary data, the evaluation and estimation of missing data, and the process of aggregation. The interim result of this process is the master program included in the Appendix which incorporates these values to predict end-of-year lake volume.

Climatologic Data

Precipitation records have been kept at Lakeview, Oregon since 1884 by various observers. Daily and monthly total rainfall (in inches) is published in Climatological Data for Oregon prepared by NOAA/National Weather Service. In the very few instances where data were missing during the study period from 1946 to 1975, average monthly values were substituted. This method was chosen over Theissen polygon or arithmetic average due to the lack of nearby weather stations and the inordinate amount of effort required in creating a double-mass curve for fewer than five monthly totals out of 360 months.

The Lakeview precipitation data were entered into a computer file along with monthly mean temperature data by water year to facilitate the computation of evaporation and streamflow estimates for the year. Evaporation was calculated first by the method described by Thornthwaite and Mather (1955, 1957). This technique uses monthly air temperature as an index of evapotranspiration over the course of the year. Average monthly air temperature (^{o}C) for each month (T_a) is placed into Equation 6 to create an annual heat index (I).

(6) $$I = \left[T_{ai}\right]^{1.5}$$

A third degree polynomial function (b), using the annual heat index, is then derived (Equation 7) to be used as an exponent in the calculation of monthly evapotranspiration (cm/month) (E_t) in Equation 8.

(7) $$b = 0.49 + 0.0179I - 0.000771I^2 + 0.000000675I^3$$

(8) $$E_t = 1.6 \left[\frac{10T_a}{I}\right]^b$$

This value was then corrected for monthly sunshine duration which is a function of latitude and the month of the year. The Thornthwaite methodology was chosen over the more accurate energy budget methods simply due to the lack of wind and radiation data in the basin, such as are required in Penman's (1961) calculations.

Although primarily a measure of evapotranspiration (ET), the Thornthwaite method may be used to estimate evaporation from a water surface. Penman (1961) defined the ratio between potential ET (E_t) and evaporation from an open water surface (E_o) as a fraction between 0.7 and 0.75. This means that on average, estimates of potential ET are 25 to 30 percent lower than actual evaporation from a water surface.

Actual evaporation was calibrated in a different way for this study. A vegetative water use study conducted by the California Department of Water Resources from 1959 to 1962 required the installation of an evaporation pan at Davis Creek, California (Merrill 1965). Published data shows measured ET from dry rangeland in inches for the four-year period.

Thornthwaite potential ET (E_t) derived from monthly Lakeview temperature data was correlated with monthly actual ET (E_a) from the agricultural study and a highly significant linear relationship was drawn, resulting in a correlation coefficient of 0.94 (See Figure 9). The figure shows the consistent but proportional underestimation of the

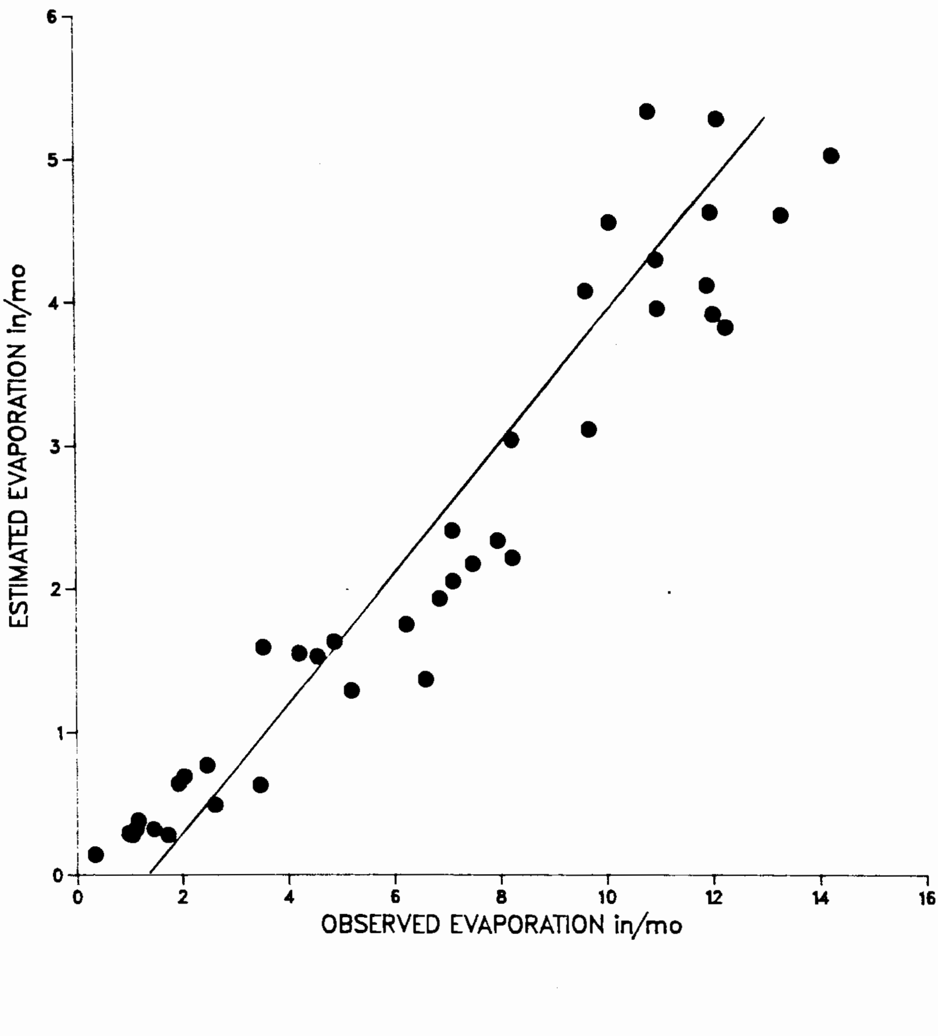


Figure 9. Thornthwaite (Y) estimate of evaporation versus actual (X) measured evaporation.

Thornthwaite method relative to observed ET for the period.

Penman's ratio, an intermediate 0.72, was then applied to the corrected Thornthwaite values to convert ET to evaporation from the water surface for monthly totals, to be summed for an annual total. Annual evaporation values used previously by Waring (1907), 48 inches, Sanderson (1966), 42 inches, and Phillips and VanDenburgh (1971), 42 inches, all compare favorably with the estimate presented in this study of 41.21 inches average. Various methods and time periods are responsible for this range in values.

Streamflow Data

Streamflow records were obtained from the USGS Water Resources Division in Portland, Oregon, the Oregon Water Resources Department (1978), and the California Department of Water Resources at Red Bluff. Streamflow record for the full period of interest exists at only two stations on the Oregon side of the basin, Cottonwood Creek and Drews Creek. Partial records are listed in Table II for both states.

Completeness of data reporting varies widely from one station to another with several California sites reporting only summer flows. The determination of annual streamflow for these streams required the re-creation of winter flows by regression with nearby streams, as described below. Other streams on both sides of the basin were excluded from analysis if 1) they were tributaries to gaged sites

TABLE II

STREAMFLOW RECORDS FOR THE GOOSE LAKE BASIN USED IN THIS STUDY

	Period of record	Drainage area (mi^2)
California		
Cottonwood Creek	10/59 to 9/75	9*
Davis Creek	10/59 to 9/75	24*
Lassen Creek	10/61 to 9/75	27*
New Pine Creek	9/58 to 9/75	14*
Willow Creek	10/61 to 9/67	33*
Oregon		
Bauers Creek	10/46 to 9/51	65
Camp Creek	10/46 to 9/75	30*
Cottonwood Creek	10/46 to 9/75	33
Drews Creek	10/46 to 9/75	212
Dry Creek	10/46 to 9/51	25
Thomas Creek	10/46 to 9/58	28
		500 total

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* - areas determined by planimeter digitizing.
Source data: U.S.G.S. and California DWR, miscellaneous records

mentioned above or 2) the documented period of record terminated prior to 1946. In the first case, data from tributary sites do not add to the volume of water entering the lake, although monthly values may be used in reconstruction of missing downstream values. In the second case, short term records are from the late-1920's, a period of low flow and are therefore not representative of average conditions during the control period, 1946 to 1975.

Reconstructed seasonal flow for the California partial records (Davis, New Pine, and Cottonwood Creeks) was based on the monthly and seasonal streamflow of year-round stations nearby. For this reconstruction, Lassen, North Fork Davis, and Willow Creeks were used as the year-round reference stations. Monthly means were calculated for the three reference stations for the period of record of each (i.e., all Januaries averaged, all Februaries averaged). The monthly means were summed for "winter" and "summer" seasons (first and second halves of the water year), and the winter to summer ratio was calculated at each station. The ratios ranged from 0.33 to 0.50, probably an indicator of differing snowmelt and baseflow characteristics in each subbasin.

The winter/summer ratio was applied to summer runoff figures of the partial stations to derive estimated annual runoff for that portion of the basin. In three instances, there were less than six months of available record in a given year. The runoff for that year would be incremented by the winter/summer ratio and then multiplied by 1.08 to append the average month to the total. A brief rundown of the specific approaches used to derive annual runoff for each of these streams follows.

A discontinuous record from 1959 to 1975 was used to extend annual runoff estimates for Cottonwood Creek, California. The mean and standard deviation for each month utilize data from all available years of record. As is the rule in this region, the coefficient of variation (s/x) is high but tends to be less than 1.0 (mean $CV_{6mo.} = 0.96$). For this particular analysis, Willow Creek was chosen for reference due to its physical proximity. Annual runoff figures for Cottonwood Creek used in basin regression equations were calculated for 10 of the 17 years available.

The presence of a year-round station on the North Fork of Davis Creek makes the extrapolation of the Davis Creek annual values perhaps the most reliable of the three. The period covered at the North Fork site, from WY 1961 to 1967, shows a seasonal change in CV from 0.39 in the winter to 0.65 in the summer -- mostly due to snowmelt and late-spring precipitation peak timing. The CV for the Davis Creek station is lower for the summer period showing, as one might expect, the downstream buffering effect of other tributaries and baseflow conditions on runoff variability. The winter/summer ratio for the North Fork site was 0.33, the lowest of the three reference sites, likely due to later-season snowmelt. Using the ratio, fourteen years of runoff were estimated for the downstream site.

The New Pine Creek annual discharge was probably the most difficult to evaluate because of its smaller subbasin size and distance from the other previously identified subbasins. The summer record is fairly complete and the CV is quite low (0.42) which also indicates a fundamental difference between this and other sites. Given that local precipitation and temperature patterns do not vary significantly along the east side of the basin, a low summer CV is interpreted to indicate a larger baseflow component.

One would expect to see a similar phenomenon in the Cottonwood subbasin from which record the New Pine Creek record was extended, but it is not there. The only major difference in the drainage is lithologic -- Quaternary alluvium (Qal) occupies the upper half of the New Pine Creek subbasin, but none appears in the Cottonwood drainage (CDWR 1963, Plate 3). This sediment body must act as a reservoir being recharged during the winter months and contributing to baseflow during the late summer, early fall.

Sixteen years of record were reconstructed by combining the winter/summer ratios of Lassen (0.5) and Willow (0.40) Creeks, effectively multiplying summer flow by 1.45 to create the annual record. Reconstructed flow did not correlate significantly with Cottonwood Creek even to the 0.95 level. Because of its unpredictable record, it will be included within the 1.80 coefficient which represents the ungaged areas.

Streamflow on the Oregon side of the basin does not require the seasonal reconstruction required for several of the California stations. Drews Creek, where gaged, represents the largest drainage area covered by one gaging site (212 mi^2). Since 1912 the flow has been regulated by Drews Reservoir which has a capacity of 62,550 acre-feet, roughly equivalent to the average annual runoff of the subbasin (based on 47 years of record). This regulation makes the use of this long-term record less reliable for basin-wide calibration due to the large storage effect. The actual flow into Goose Lake from Drews Creek is further affected by diversion into North Drews Canal, used for irrigation.

Cottonwood Creek has a record nearly the same length as Drews Creek and its annual flow is only minimally regulated by Cottonwood Reservoir, capacity 7,540 acre-feet (USGS 1979, p. 53). The annual summation of runoff allows for the use of records with some reservoir regulation if there is no diversion because storage only delays runoff -- the total runoff in a given water year should be the same. Conveniently, reservoirs become empty at the end of the water year and fill over the course of the succeeding water year. Because of these characteristics. Cottonwood Creek was chosen as the long-term reference stream for the study.

Modelling Annual Basin Streamflow

Records were acquired for Cottonwood Creek from the USGS Water Resources Division, Oregon District which summarized mean flow in cubic feet per second (cfs) on an annual basis for the period of record. The rate was converted to total acre-feet runoff per given water year. Other short-term records were prepared in the same annual format. Those years common to both Cottonwood and the partial record were entered into a least squares computation to derive a correlation between subbasin runoff values.

By this technique an equation was defined for each stream to describe its typical relationship to the long-term Cottonwood runoff. A measure of the tightness of fit, the correlation coefficient (r), was also computed for each stream. Also shown is the percentage of the variance in X explained by Y, expressed by the coefficient of determination (r^2). In general, the correlations throughout the basin were very good (See Table III).

The lowest correlations were for those streams whose winter records needed to be estimated relative to nearby streams. The lower coefficient at Willow Creek is probably due to subbasin conditions and a short period of common record (6 years) rather than the expected decrease in

TABLE III

STREAMFLOW EQUATIONS AND COEFFICIENTS OF DETERMINATION FOR SUBBASINS RELATIVE TO COTTONWOOD CREEK, OREGON, ANNUAL DISCHARGE IN ACRE-FEET.

California		
Cottonwood Creek	$y = 9.6196(x^{0.5414})$	$r^2 = 0.50$
Davis Creek	$y = 4.3754(x^{0.7770})$	$r^2 = 0.47$
Lassen Creek	$y = 0.5736x + 1830.7111$	$r^2 = 0.86$
New Pine Creek	------	$r^2 = 0.25$
Willow Creek	$y = 0.4083x + 1089.6173$	$r^2 = 0.71$
Oregon		
Bauers Creek	$y = 0.8507x + 965.1543$	$r^2 = 0.91$
Camp Creek	$y = 0.1830x + 1542.6811$	$r^2 = 0.78$
Drews Creek	$y = 3.6584x - 16629.395$	$r^2 = 0.83$
Dry Creek	$y = 0.6235x - 293.8325$	$r^2 = 0.90$
Thomas Creek	$y = 0.6907x + 1045.5180$	$r^2 = 0.93$

Source data: USGS and California Dept. of Water Res. streamflow data, 1922-1982.

correlation with distance. In contrast, Lassen Creek, with a 14-year period of record, has a very high coefficient of determination ($r^2 = 0.86$). This is likely due to the longer common record with Cottonwood Creek, Oregon.

Lake-Level and Volume Records

Observations of the surface elevation of Goose Lake have been made since the 1830's by many interested parties including the USGS Water Resources Division, the Oregon Water Resources Department, and the California Department of Water Resources. Harding (1965) reported many of these earlier observations through a review of historical documents. The frequency of observation of lake-level to an established datum has varied from weekly (late 1950s) to monthly (mid 1940s) to semi-annual/annual reports at other times. Recorded observations before and during World War II were rarely made, which helped to define the study period chosen. A composite historical record of wetter and drier records is documented in the California Water Quality Control Policy Report (1966).

Most observations made by the three water agencies mentioned above were done by running levels from a known elevation, usually a surveyed benchmark, to the lake surface and back, then determining the elevation difference to 1/100 of a foot. This accuracy seems artificial given that waves on the lake even during rare calm periods have heights on the order of several tenths of feet.

Lake surface area was calculated in a bathymetric survey by the California Department of Water Resources (1960). This surface is critical to the estimation of volumes of evaporation and precipitation occurring at the lake surface. The given values were then entered into an elevation-volume-area program developed by the Corps of Engineers for reservoir regulation. Using a conic approximation of volume, a series of nested cones depict the volume and area at each contour.

Model Construction and Calibration

A program was written in BASIC to access actual or synthesized component values for each of the water years from 1946 to 1975. Annual precipitation (inches) at Lakeview was converted to a volume of precipitation given an antecedent lake volume or surface area value. Thornthwaite estimate of evaporation, corrected for basin and pan conditions was used, given the antecedent lake surface area, to determine the evaporated volume from the lake. Streamflow for Cottonwood Creek was used as an index stream from which basin runoff was estimated according to the regression equations listed in the previous section. Each component for a given water year was then fed into the water balance equation (9, below) to produce a year-end lake volume.

(9) $$V_t = V_{t-1} + I_s + P - E_o$$

where V_t = Year-end volume, year t
V_{t-1} = Previous year-end volume
I_s = Inflow, streams
P = Precipitation
E = Evaporation

The model was run with the parameters as described above (program name MASTER.BASIC) with the actual antecedent volume entered for each annual iteration. The correlation coefficient for annual versus estimated year-end volumes for the 30-year period was 0.97, explaining 93 percent of the variance (See Figure 10). This first run did not include an estimate of irrigation withdrawal which could show up as a persistent additive error. The fit, given the reconstructed streamflow and potential error in other components is remarkably good, as the Figure shows.

The next test was to let the year-end volume derived by the model be the antecedent volume for the following year rather than substituting the correct (observed) volume. In this manner consistent error in one of the components will be cumulative, leaving only random error.

The model was re-run with only the first year antecedent volume known, the rest were generated by each annual budget iteration. The results, shown in Figure 11 were quite revealing. The period during the late-1940's shows minimal difference between estimated and observed volumes. This was the period during which many of the

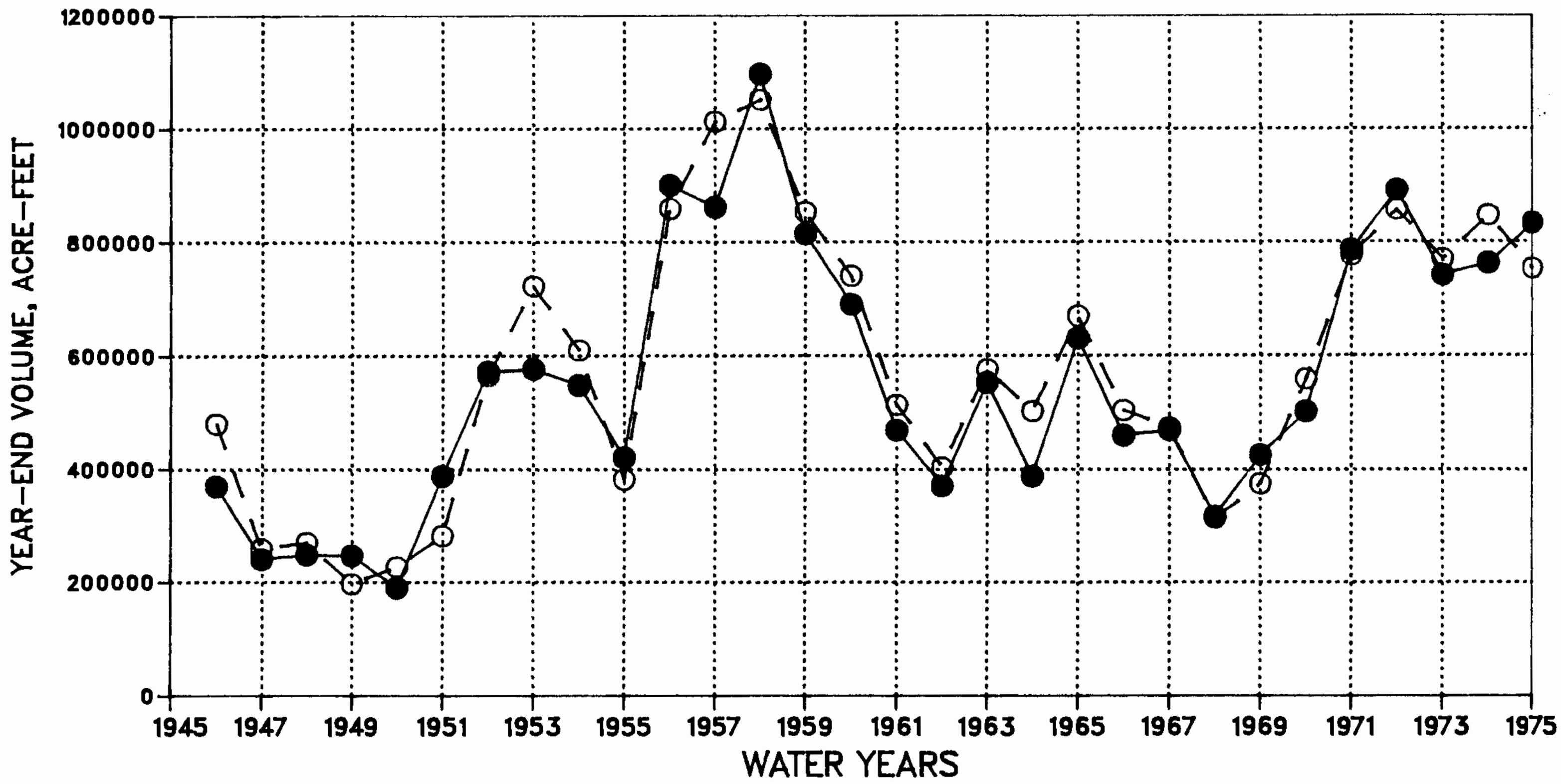

Figure 10. Actual (solid line) and estimated (dashed line) year-end lake volumes with corrected antecedent volume inputs.

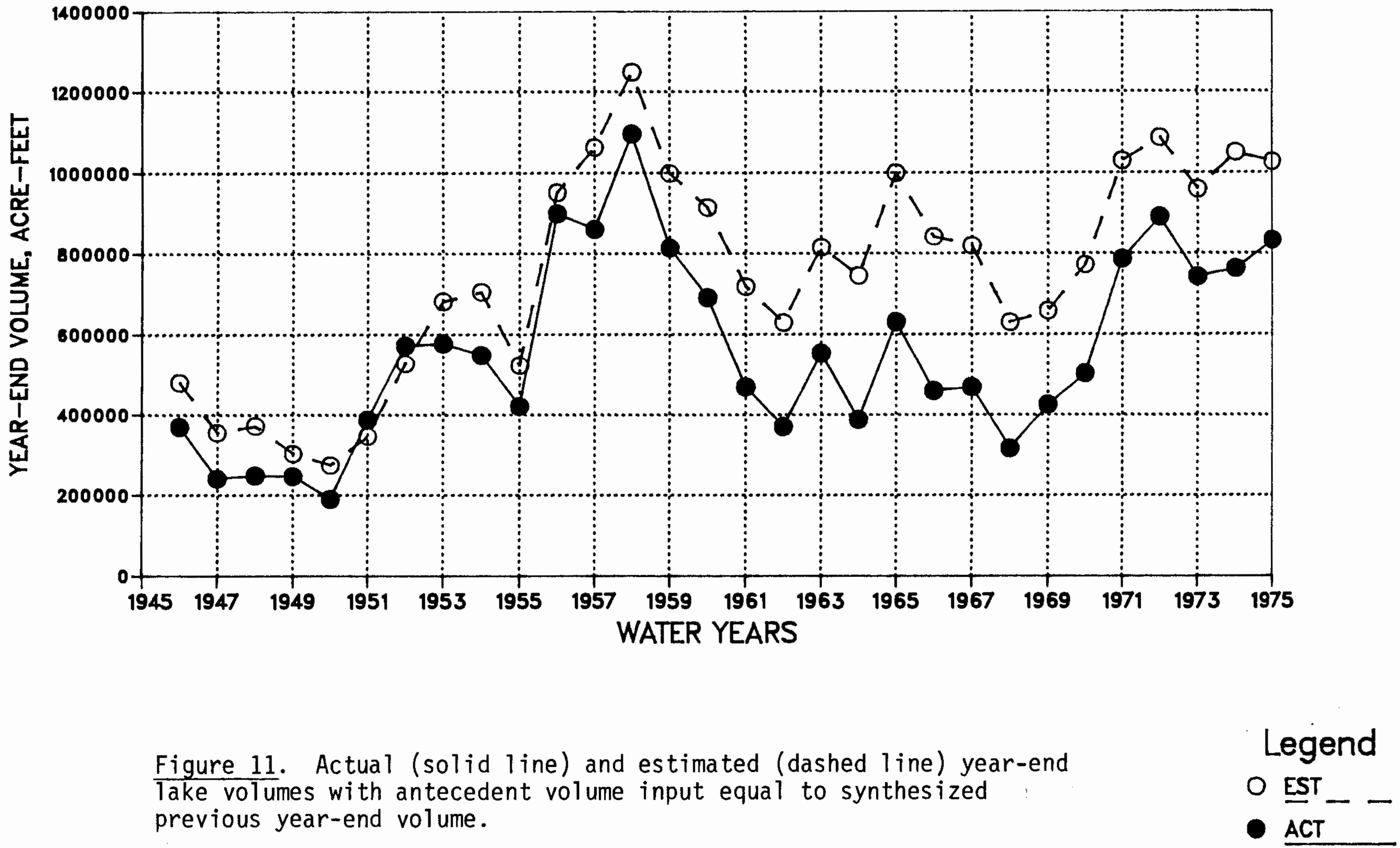

Figure 11. Actual (solid line) and estimated (dashed line) year-end lake volumes with antecedent volume input equal to synthesized previous year-end volume.

short-term stream-gages were active, and thereby was also the period for which the regression equations against Cottonwood Creek runoff were the most applicable. The apparent trend shows an overestimation of about 100,000 acre-feet early in the study period increasing to a plateau at about 250,000 acre-feet at the close of the period. This trend is more than simply a cumulative systematic error because it does, in fact, plateau, rather than keep increasing with time as a cumulative error should do.

The shape of this curve (Figure 12) approximates that defined by increasing irrigation withdrawal from surface water sources to a peak (maximum utilization) withdrawal in the late-1960's after which more groundwater was put to use. The magnitude of the error, however, does not appear to be due to only irrigation use because nothing near 200,000 acre-feet of water is consumed by crops in the basin. The beginning error, approximately 100,000 acre-feet is likely due to a systematic overestimation of yield from the non-gaged streams in the basin -- the largest potential error generator in the model. If the estimate of annual runoff were scaled down (the 1.8 coefficient) to produce approximately 100,000 acre-feet less water, then the residual trend line would be largely attributable to irrigation withdrawals as an increasing function with time.

One further consideration is that a certain amount of irrigation was occurring during the 1940's and must be

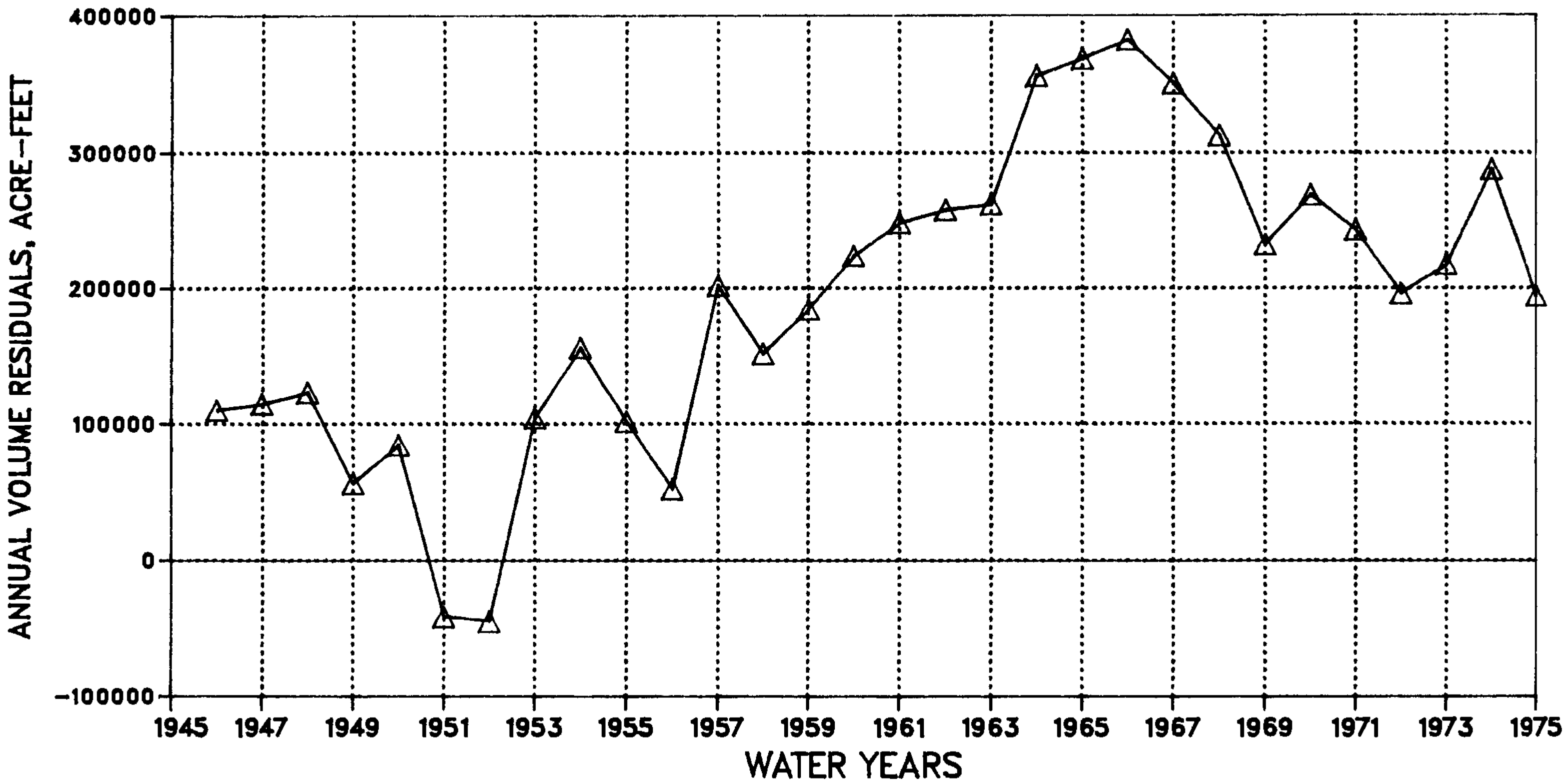

Figure 12. Plot of difference between actual and estimated year-end lake volumes shown in Figures 10 and 11.

corrected for in the reconstruction of earlier records when little or no withdrawal occurred. Estimates of water-use by irrigation document about 30,000 acre-feet diversion in the mid-1950's (CDWR 1982) and about 70,000 acre-feet during the current period (SCS 1978) with little diversion prior to the turn of the century. This would yield a correction curve similar to that shown in Figure 13. Although the curve reflects neither availability nor variable consumption of water during a given year, the trend is defined for calibration purposes.

This curve was applied to the year-end estimates of streamflow such that 1940 is treated as zero difference (calibration of streamflow occurred at this level of withdrawal). A new series was generated which more closely resembles the actual lake volumes seen. Figure 14 shows that the estimate (dashed line) is neither consistently above nor below actual curve, as occurred in the previous run (Fig 10) where the estimated year-end volume was introdiced as the next year's antecedent volume. The correlation coefficient improved from 0.90 to 0.94 and the estimated series explained 88% of the variance of the process.

Application of the irrigation curve diminished the need for amending the runoff coefficient, although an average annual over-estimation of about 20,000 acre-feet still was present. Figure 15 shows the volume difference to

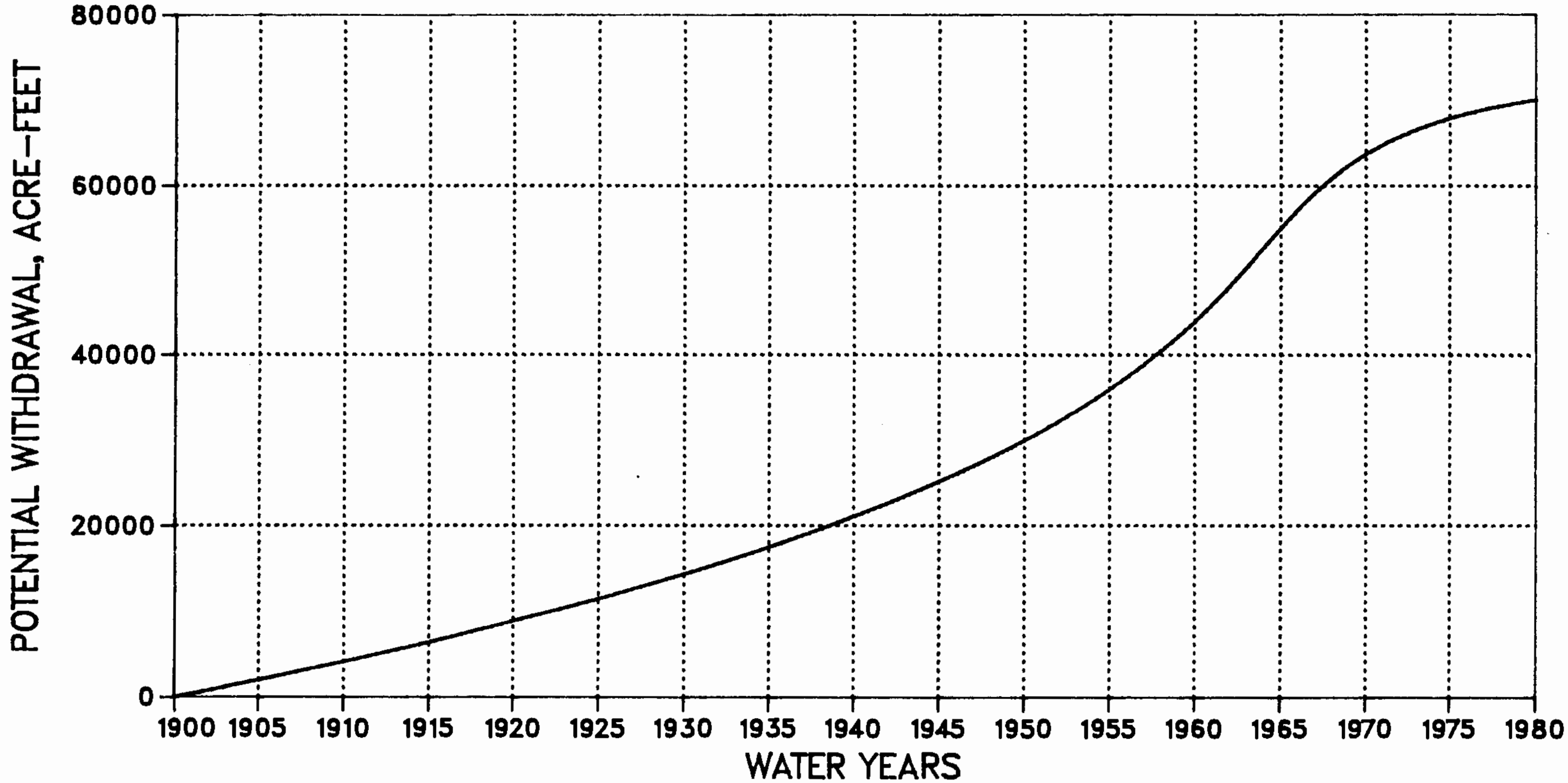

Figure 13. Time curve of potential consumptive surface water use in Goose Lake Basin.

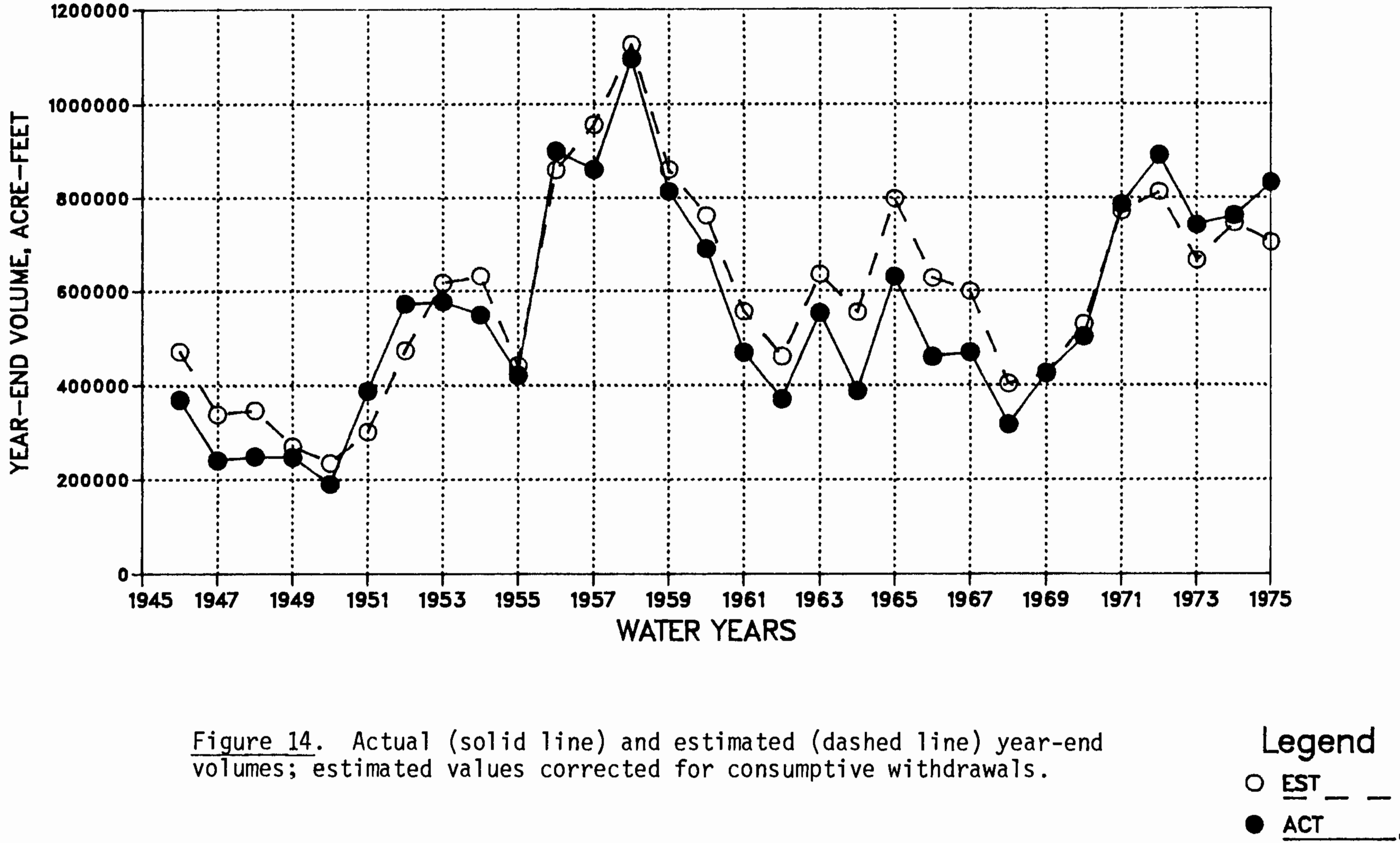

Figure 14. Actual (solid line) and estimated (dashed line) year-end volumes; estimated values corrected for consumptive withdrawals.

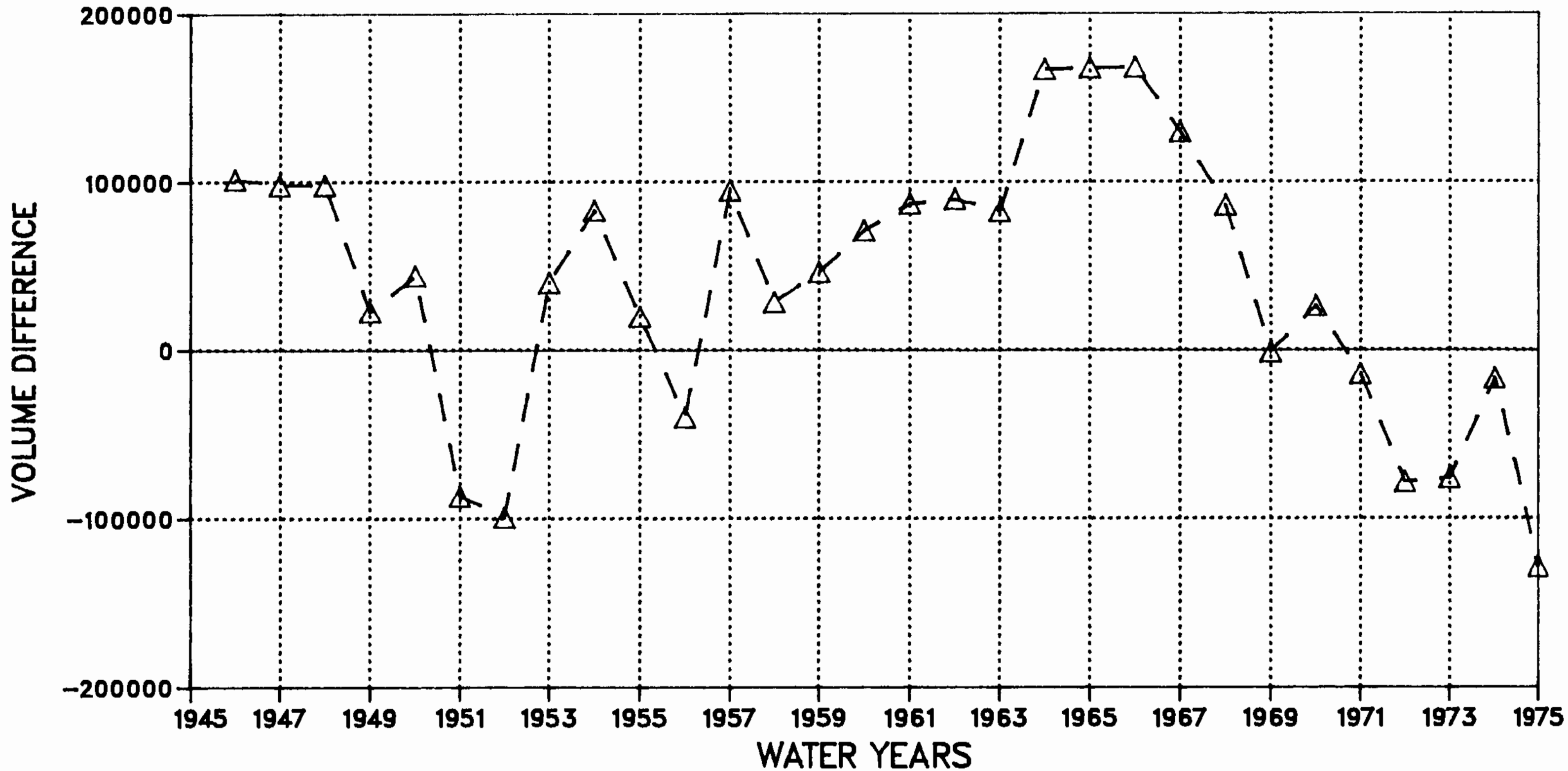

Figure 15. Volume difference between actual and corrected estimates of year-end lake volumes.

be more evenly distributed about the zero-change line. The source of this residual error is unknown and fairly random in time, as the figure shows. Certain periods of over-estimation may represent irrigation or evaporation overestimation which was less than was synthesized, or precipitation and streamflow which was greater than estimated. The fact that the difference plot does not have a well-defined trend makes its explanation by a specific parameter nearly impossible at this level of investigation. For now, the calibration must stand with this remaining margin of error. Error in calibration may be reduced if parameters such as irrigation withdrawal, total streamflow, and evaporation values were known for the period.

Evaluation of Calibrated Model

It has been demonstrated, with an unexpectedly high degree of accuracy, that an annual lake-volume water budget model can be developed and a majority of the natural process be explained, given certain measured and synthesized inputs for a series of years. The incorporation of human modification (diversion) into the model served to improve further the accuracy of the estimate not only on a year-to-year basis, but also as part of a self-generating series dependent only on the initial year antecedent volume. Residual error was minimized and changed from an increasing error to a largely random error in time, unattributable to specific parameters.

This process is now ready for application using a longer environmentally-sensitive series (tree-rings) to drive the model prior to the present well-monitored period. Application of this process also seems extremely well suited to other nearby basins where environmental data may exist or be synthesized well enough to model lake level change. In this way a better understanding of recent high water events may be effected.

CHAPTER V

RECONSTRUCTION OF LAKE-LEVEL RECORDS USING TREE-RING DATA

The extension of the water budget model described in Chapter IV beyond the study period requires a detailed analysis of the interaction between precipitation, runoff, and tree growth in the basin. The first important relationship, although not used directly in the model, is the dependence of streamflow upon precipitation. The other two relationships of greater importance to the reconstruction model are tree-ring to runoff and tree-ring to precipitation comparisons, both of which are water related.

Environmental Relationships

The dependence of streamflow upon precipitation has long been recognized, especially in terms of storm runoff and other short-lived events. The long-term relationship between precipitation and runoff, as a seasonal or annual value, becomes increasingly obscured due to the effects of infiltration of meteoric water not lost as overland flow. This effect is particularly pronounced in arid regions where precipitation tends to occur as a result of convectional storms which produce rainfall at a rate much higher than the infiltration capacity of the soil, leading to a large immediate runoff. Rarely in an arid region will precipitation occur at a rate less than the infiltration capacity of the soil, except in low-lying hollows, depressions, or intermittent streamcourses where ponded water may be introduced into the ground at the infiltration capacity.

The high desert of Oregon, as is found in most of the Goose Lake basin, may receive a considerable amount of its precipitation by way of snowfall associated with winter frontal systems. This can melt at or below the infiltration capacity of the soil and enable groundwater recharge at rates greater than at other times of the year. This complicates the annual runoff response to precipitation of all forms since baseflow (largely groundwater discharge) can be a large component of runoff during the summer months. Before a model of basin response can be constructed, all the various elements leading to the annual budget must be examined.

Tree-Ring Data for the Goose Lake Basin

The Laboratory of Tree-Ring Research at the University of Arizona has been collecting and publishing tree-ring chronologies for many years. Two publications -- Drew 1975 and Stokes, et al 1978 -- present over 60 selected sites where tree rings have been obtained, corrected for growth width variation, and matched against other trees on the site for cross-correlation. The annual ring widths for the site are then transformed into annual indices by representing a given year's width as a percentage of normal, 100 representing the mean value. A number of statistics are derived from the indices at each site which give an indication of the sensitivity of the site to environmental stress. Generally speaking, a low serial correlation, a low standard deviation, and a high mean sensitivity indicate that the site is more desirable for use in precipitation or streamflow reconstruction.

The data used in this thesis were collected by M. L. Parker and are published by the Laboratory of Tree-ring Research (See Appendix for the Lakeview ring series). The ring width indices used in this study were obtained from ponderosa pine trees on a southeast-facing site on the west side of the basin at an elevation of 6000 feet, which approximates mean basin elevation. The statistics published with these data indicate a serial correlation of 0.583, a standard deviation of 0.224, and a mean sensitivity of 0.161 (Drew 1975). The moderate serial correlation indicates a level of persistence in the series, common to most ring index series. This occurs because the trees are responding to changes in available soil moisture which is a function of the immediate and preceeding years. Hence one would expect the tree ring indices to appear as a smoothed series compared to preciptation or streamflow which is far more variable from year-to-year.

The ring width indices have been prepared from 1421 to 1964 and are displayed in a graphic form in Figure 16. The time series plot shows the annual variation in ring indices at the Lakeview site. Close examination of the plot reveals numerous periods of both above and below normal tree growth. It is important to note that trees tend to be more sensitive to drought than surplus moisture and have been used as indicators of both annual and seasonal precipitation and streamflow, as described in Chapter III.

Trends in the tree-rings during historical periods (1830 to 1964) appear to parallel general water availability documented by residents (Harding 1965). The drought periods of the 1840's and 1920's-'30's are well demonstrated by the tree-ring indices. Periods of abundant moisture from 1908 to 1915 and since 1940 are similarly tracked. Average ring widths from 1850 through 1885 correspond to average or greater than average water supply in the area.

The anomalous series values of the tree-ring indices since 1940 has been addressed by several authors. Phipps (1983) has identified a growth decline for spruce in the northeastern U.S. since 1950. Phipps believes that increased environmental stress is responsible, in the form of acidic precipitation, disease, insect damage, crown competition, and other natural aging processes. Puckett (1984) has also noted a similar decline in red spruce (Picea rubens Sarg.) in New

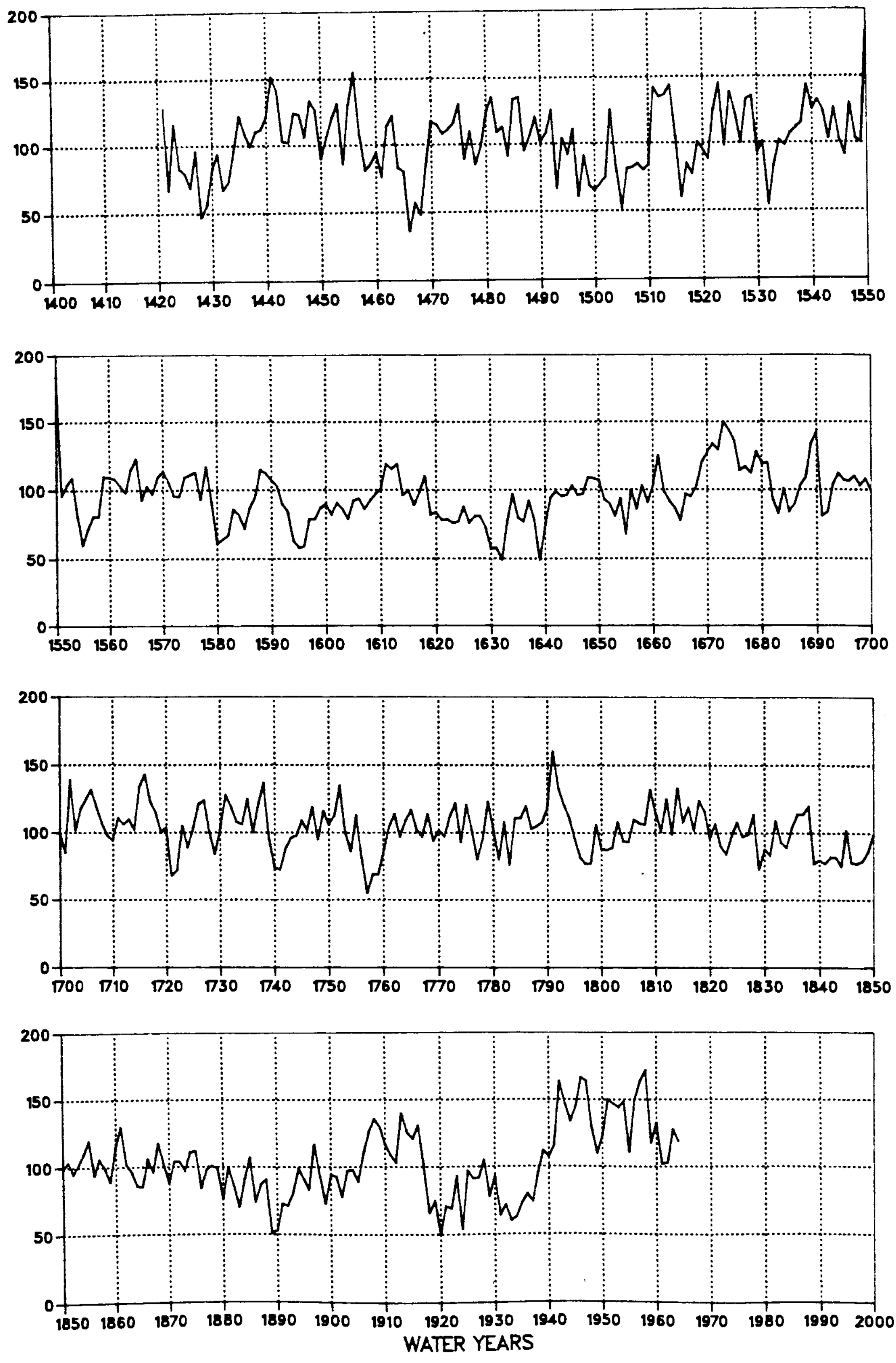

Figure 16. Tree-ring indices, Lakeview site, collected by M. L. Parker (Drew, 1975).

Hampshire, and cites similar possible reasons for the decline. Most importantly, Puckett observed that the response of the spruce trees to climate has changed because of the increased physiological stress.

The anomaly observed with the Lakeview ring indices is opposite to that observed by Phipps and Puckett and appears to explainable by environmental conditions. Precipitation, as measured at Lakeview from 1913 to 1939 (water years) averaged 11.24 inches, whereas for the 1940 to 1964 period, the totals averaged 15.65 inches, or 39 percent higher. The higher tree ring indices between 1940 and 1964 therefore appear to be a legitimate physiological response to the more abundant moisture of the period and not due to other environmental controls.

Unity in Environmental Response

A further illustration of the similarity between ring width and precipitation indices is shown in Figure 17. Plots of cumulative departure for both series show a profound deficit in available moisture (negative slope) from 1917 to 1934. Tree-ring index response turn-around appears to lag behind precipitation by about three years, owing to residual soil moisture. Ring index responses in 1948, 1954, and 1960 show similar lags for the same reason.

A third plot of cumulative deviation of runoff for Cottonwood Creek shows a similar response to declining

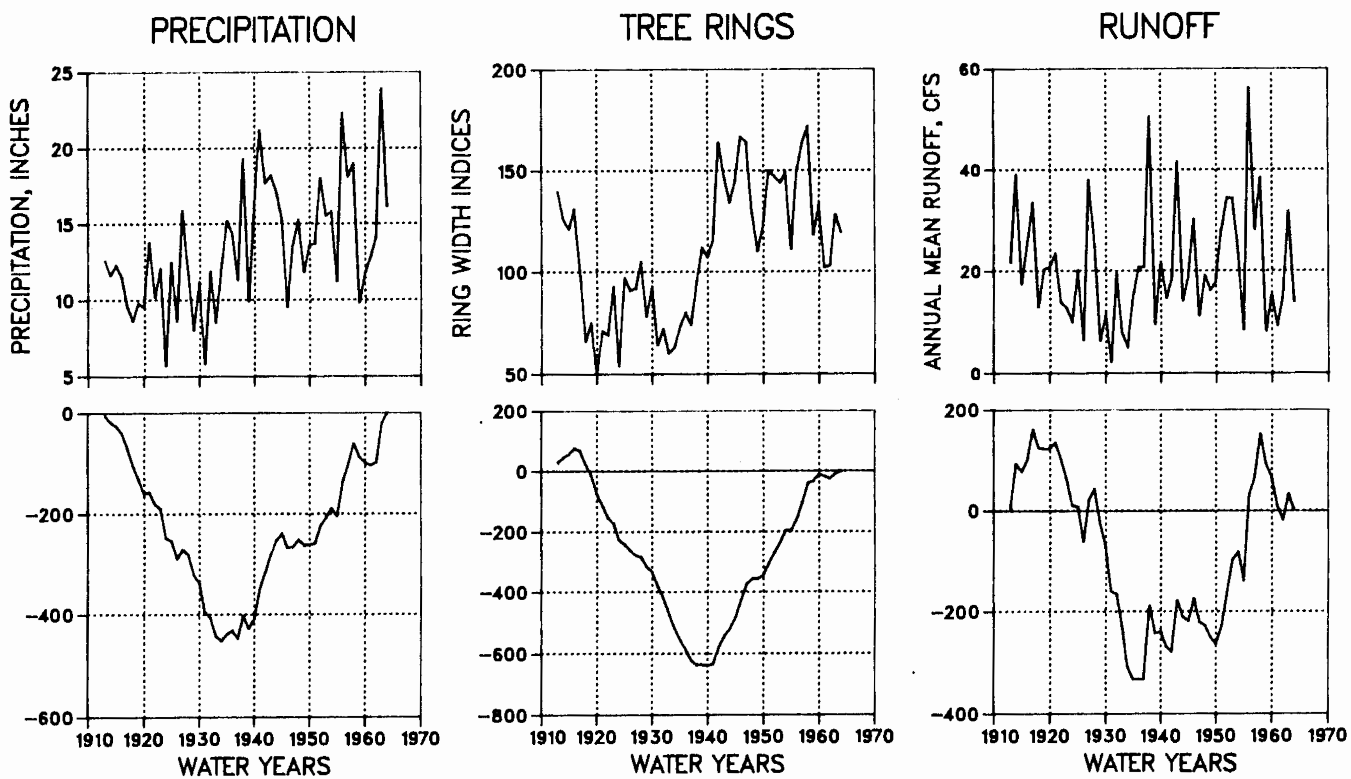

Figure 17. Time series plots of annual (water year) precipitation, tree-ring indices, and runoff for Goose Lake Basin.

precipitation. The decline begins in 1921 and ends in 1935, interrupted by a brief positive episode during 1927-28. This anomaly is seen in the precipitation record by a short positive turn, and in the tree-rings by a lessening of the negative slope. The more variable nature of annual runoff values is responsible for the more jagged or "responsive" cumulative deviation curve. Although cumulative deviation plots may not be the best means to compare time series, a cursory sensitivity of tree-ring indices to both precipitation and runoff can be demonstrated.

Synthesis of Precipitation from Tree-ring Indices

The fact that tree-rings do respond to precipitation during a given year has been shown with various degrees of success by many authors (Schulman 1951, Ferguson 1959, Fritts 1966, Julian and Fritts 1968, Fritts 1974). The main obstacle to a clear correlation between rainfall and tree growth has been the sensitivity of trees to residual moisture from previous years. To demonstrate this phenomenon, annual (water year) precipitation (transformed to indices) at Lakeview was compared to ring width indices for the 52-year period from 1913 to 1964. A correlation coefficient of 0.56 was obtained for concurrent annual values. This explains only 32 percent of the variance in the process (See Table IV). Precipitation indices were then weighted for the curent and two previous years and were regressed against the ring

TABLE IV

CORRELATION TABLE FOR ANNUAL LAGGED PRECIPITATION INDICES DERIVED FROM ANNUAL TREE-RING INDICES. FIRST COLUMN REPRESENTS THE CURRENT YEAR WHEREAS THE SECOND AND THIRD COLUMNS REPRESENT IMMEDIATELY PRECEDENT YEARS.

t	t-1	t-2	r^2	r
1.0	0.0	0.0	0.317	0.56
0.9	0.1	0.0	0.356	0.59
0.8	0.2	0.0	0.394	0.63
0.7	0.3	0.0	0.425	0.65
0.6	0.4	0.0	0.444	0.67
0.6	0.4	0.2	0.472	0.68
0.5	0.4	0.1	0.492	0.70
0.5	0.4	0.2	0.503	0.71
0.5	0.4	0.3	0.500	0.71
0.5	0.5	0.2	0.476	0.69
0.5	0.5	0.3	0.475	0.69
0.5	0.5	0.4	0.467	0.68
0.5	0.5	0.5	0.456	0.67
0.4	0.6	0.0	0.431	0.66
0.3	0.7	0.0	0.400	0.63

width index for a given year. As Table IV shows, the correlation coefficient improves to a maximum value of 0.71 where the current and two preceeding years were weighted 0.5, 0.4, and 0.2 respectively such that:

(10) $$RI_t = f(0.5PI_t + 0.4PT_{t-1} + 0.2PI_{t-2})$$

where RI_t = Ring index for year t

PI_t = Precipitation index for year t.

Whereas the synthesis of a ring width index from three consecutive precipitation indices is both straightforward and a reliable process (explaining over 50% of the variance), the reconstruction of precipitation from tree rings is far more complex, as Equation 11 shows:

(11) $$RI_t = f(0.5PI_t + 0.4PI_{t-1} + 0.2PI_{t-2})$$

$$0.5PI_t = f(RI_t - 0.4PI_{t-1} - 0.2PI_{t-2})$$

$$PI_t = f(2RI_t - 0.8PI_{t-1} - 0.4PI_{t-2})$$

To determine a precipitation index for a given year, not only the ring width index but the preceeding two precipitation indices must be known -- an impossible situation if records are to be reconstructed prior to precipitation record-keeping. One possible approach to this problem would be to select an average period of tree ring growth and to assume that precipitation indices for two consecutive years were near average values. The error inherent in correctly estimating the values of two consecutive precipitation indices is high due to the high variability in the precipitation series, and therefore would not be very reliable.

The error associated with the estimation of one precipitation index, however, would be considerably less and could provide an input into a two-year weighted equation:

(12) $$RI_t = 0.6PI_t + 0.4PI_{t-1}$$

$$PI_t = 1.6667RI_t - 0.6667PI_{t-1}$$

which yields the highest correlation coefficient for a process with two time variables. This equation was tested for the 1913-1964 period correlating actual with estimated precipitation indices, and produced a correlation coefficient of 0.62, significant for N-2 degrees of freedom at the 0.99 level. The problem remains, however that an actual precipitation series does not exist prior to 1913 and that an estimate of precipitation for years t-1 or t-2 does not relate to the actual environmental response.

The reconstruction of annual precipitation at Lakeview from annual tree-ring indices should rely as much as possible upon the immediate year's tree-ring value to avoid the complex lag phenomena discussed above. The precipitation series also reflects the cumulative effects seen in the tree-ring series as was given in Figure 17.

A better relationship exists between the annual values of cumulative departure for tree-rings and precipitation.

Comparing the annual values associated with the curves illustrated in Figure 17, a correlation coefficient of 0.92 was derived for 1912 to 1964, explaining 84 percent of the variance. This strong similarity implies that tree rings are largely dependent upon a given water year's precipitation and are therefore well suited to re-create precipitation series. By taking the tree-ring cumulative deviation values from the short period (1913-1964) and identifying a similar trend relationship with precipitation, the reconstruction of precipitation of cumulative deviation values for the 1422 to 1964 period for precipitation is simplified. The cumulative departure for year t is defined as the cumulative departure for the year t-1 plus the departure for year t:

$$CD_t = CD_{t-1} + D_t \tag{13}$$

The cumulative departure for precipitation is a function of the cumulative departure of the tree rings such that:

$$CD(P)_t = CD(T)_t(0.541) - 84.06. \tag{14}$$

The annual departure is the cumulative departure minus the cumulative departure for the previous year. Therefore, the definition of departure as being the index for year t minus the mean (assumed to be 100) yields the precipitation index:

(15) $$D_t = I_t - M$$

$$I_t = D_t + M.$$

This index may now be converted to an actual value as a percentage of the mean.

Although the correlation between the cumulative departures of tree-ring and precipitation indices is high, the correlation between the annual departures is somewhat lower, as are the index and reconstructed annual values. The correlation between the departures -- in effect the slope of the cumulative departure curve between years -- produced a correlation coefficient of 0.56, and explained only 32 percent of the variance. This method approximates the straight correlation of indices but preserves the environmental sensitivity of the cumulative departure series.

The reconstructed precipitation values for the 1913-1964 period were then compared with actual values. The direction and magnitude of error was examined for each year and an average arithmetic error of +1.28 inches was derived with the standard deviation of the errors equal to 3.27 inches. This correction factor was then applied to the synthetic precipitation values for the entire reconstructed record, 1421 to 1964 such that the means of the actual and reconstructed values were roughly the same.

The adjusted precipitation series has a mean of 13.45

whereas the original has a mean of 13.62. The reconstructed series has less sensitivity to higher values than lower values, the maximum errors being 5.75 and 3.20 inches respectively. Sensitivity to drier conditions is an attribute typically more important to water supply analysis. Therefore, this technique is better suited for drought sensitivity than for wet year recurrence -- an extreme event rarely seen in tree rings.

In summary, several means of reconstructing precipitation from tree-ring data were tested. After converting the annual precipitation values to indices for the common period, 1913 to 1964, a least-squares analysis produced a correlation coefficient of only 0.56 with ring-width indices. Examination of the cumulative departure curves of both tree ring and precipitation indices demonstrated an increased similarity in temporal response. The correlation between the cumulative departure curves was quite high (r=0.92), illustrating the longer-term unity in response between the two series, not so clear on an annual basis.

Comparison between the annual slope of the two cumulative departure curves produced similar correlation statistics as the raw index comparison, but was a product of the cumulative trends in the tree-ring series, and was thereby more sensitive to trends in water availability. The technique chosen to reconstruct the precipitation series was therefore based on the correlation between the slopes of the two cumulative departure series. The precipitation index for the year was then recalculated to inches of precipitation, based on the long-term average (1913 to 1975).

Synthesis of Runoff from Tree-Ring Indices

The generation of runoff values based solely on tree rings was one of the most difficult tasks undertaken since the runoff series is far more variable and contains more extreme events than the ring series or even the precipitation series. A measure of the variability in a population is the coefficient of variation (CV), defined as the standard deviation divided by the mean. The CVs of tree ring, precipitation, and runoff indices are, respectively, 0.3, 0.29, and 0.56. This shows that the standard deviation for the runoff series is far greater relative to the mean. A wider spread is much more difficult to model if one starts with a naturally smoothed series such as tree rings.

An attempt was made to reconstruct annual runoff values in the same manner as was done with precipitation -- namely to create annual indices from the original values and then correlate them with the annual tree-ring indices. A far lower correlation coefficient was obtained (0.44) which explained only 19 percent of the variation in the series.

The random peak values generated in the runoff series are typically due to high discharge months following snowmelt periods. These peak volumes will distort the annual mean discharge simply due to the increased overland flow for a short period. Likewise, a slight increase in the percentage of precipitation which occurs as snow may further increase this trend.

This property of hydrologic time series was recognized and addressed by the Water Resources Division of the U. S. Geological Survey (1981) in Bulletin 17B which provided guidelines for determining flood flow frequency. Although primarily concerned with event probability, the document discussed the methods recommended for dealing with the skewed discharge data. Recognizing the discharge frequency curve to be a log-normal distribution, the Survey recommends the use of the Log-Pearson Type III transformation for annual flood series.

If total annual discharge series are considered to be an extension of the term "flood event", one must acknowledge the fact that the total number of events for this thesis is thereby decreased to the number of years of record. This hypothesis was tested -- namely, can discharge events be more closely modelled bytree-ring data if the series were subjected to a log-transform? Values were taken from mean discharge (cubic feet per second) for the years 1913 through 1964. The correlation between the log-transformed runoff indices and the tree-ring indices produced no great improvement in estimation over the previous regression using un-transformed data. The hypothesis that a log-transform of annual indices would be significantly better than the un-transformed estimate was therefore rejected.

Cumulative deviation curves were then examined, as was done with the precipitation values. Examination of Figure 17 shows that runoff was not as sensitive to drought as tree rings were. The periods of less-than-average sustained ring growth and runoff roughly coincide (1922-1926 and 1928-1936), but greater-than-normal runoff years are not well matched by the tree ring indices. In general, ring width indices are not good indicators of individual peak wet years. Once again, cumulative deviation values were derived and annual deviations were estimated. The correlation between the annual deviation values (the slope of the cumulative deviation curve) yielded approximately the same correlation as before ($r=0.44$, $r^2=0.20$) although the cumulative departure curves were highly correlated.

One potential remedy for this poor correlation would be to smooth the cumulative departure curve, similar to what Hardman and Reil (1936) and Keen (1937) has done. The difference between the proposed smoothing and what other authors have done before is that rather than smooth the raw series data (which may not lend itself to smoothing where a trend is not apparent) the smoothing would occur on the slope of the cumulative deviation curve, refining the trend by eliminating some of the noise inherent in the runoff series.

Two methods were chosen for smoothing the cumulative deviation plots. The first, a weighted mean (years t, t-1, t-2) with an equal weighting per year, produced a correlation between the curves which was worse than the unsmoothed data. The use of a 7-year iterative smoothing technique (nicknamed "3-RSSH") improved the correlation only marginally.

Again the translation of the curve values into the slope values reduces the correlation significantly, such that the correlation coefficient returns to approximately that value derived in the annual index correlation.

Since the smoothing of the runoff cumulative departure curve values did not improve the relationship, the log-transformed (base-10) runoff series was tested to determine if it could improve the correlation between actual and predicted discharge values. The test showed the correlation coefficient dropping to 0.42, explaining only 18 percent of the variance.

On the basis of these various approaches, it has become obvious that the use of a log-transform or smoothed cumulative departure curve does not improve prediction of runoff from tree-ring data. In fact, the relationship deteriorated. Given this conclusion, the same technique used to relate precipitation to tree-rings was chosen.

In summary, runoff indices were created for the common period (1913-1964) and were compared with tree-ring indices using least-squares analysis. As with precipitation, the plots of cumulative departure for tree rings and runoff for te period were highly synchronous but the actual annual correlation was fairly poor (r=0.44). Various smoothing techniques were applied but non improved the annual series' correlation. It was therefore decided that the use of the annual slope of the cumulative departure curves was the most reliable means of estimating runoff indices. This is the same method which was applied to the precipitation data.

It became apparent that an accurate reconstruction of lake volumes based on tree-rings was not achievable given the large margin of error associated with the development of streamflow and precipitation series from tree rings. The creation of a series of relative lake volumes did, however, seem reasonable given the similarity in cumulative departures (sensitivity) among the three data sets. This way, periods of water surplus and shortage could be identified generically and their duration, intensity, and frequency could be evaluated in a more qualitative manner.

Model Construction and Calibration

The process and program used in Chapter IV to model recent lake volume changes was modified to accept streamflow and precipitation data synthesized from tree-ring indices.

Datafiles were created contained estimated annual runoff in acre-feet for Cottonwood Creek, Oregon and estimated annual precipitation on the lake surface, for the 1422 to 1964 period.

The water budget calculation process requires an initial lake volume or elevation from which it calculates the surface area upon which precipitation or evaporation act. The volume of runoff from Cottonwood Creek is taken from the datafile for the year in question and is related to runoff throughout the basin via a family of regression equations to produce an estimate of total basin runoff. Estimated precipitation for that year is extracted from the another datafile and is converted to a volume given the calculated surface area of the lake. Evaporation, assumed to be fairly constant (41.21 inches based on the 1946-1975 average) is also converted to a volume over the lake surface. From 1900 until 1975 the estimated runoff is adjusted by an increasing volume of consumptive withdrawal not accounted for in the streamflow regression equations.

The estimated year-end lake volume is the result of the combination of the antecedent volume, the precipitation and (adjusted) streamflow volumes as positive values, and evaporation as the sole negative value. The next year's antecedent volume is set to equal the preceeding year's end volume. This process was repeated for each year from 1422 to 1964. Figure 18 illustrates the water budget calculation

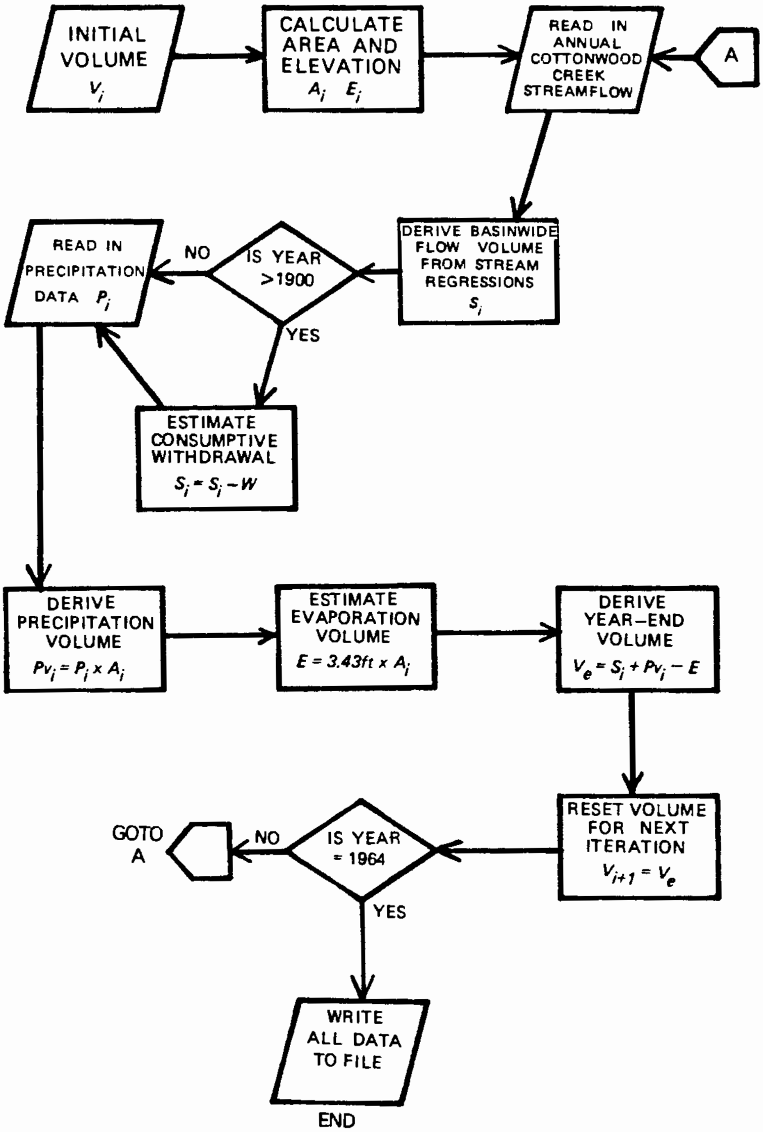

Figure 18. Schematic diagram of water budget calculation.

process.

Prior to the application of a withdrawal correction to streamflow estimates, an evaluation of the sensitivity of the model to individual component variation was undertaken. Evaporation, the streamflow coefficient, and precipitation were varied separately to examine the effect each component had on year-end volumes. It was discovered that small adjustments to all of the components (±5 percent) produced sizeable changes in the annual totals over time.

Evaporation was increased and decreased by 5 percent to demonstrate the effects of variation from the assumed evaporation value. By decreasing evaporation, "dry lakebed" (volumes less than 79,510 acre-feet) occurred 27 years out of the 543 years of record in eleven episodes of less than five years' duration. Increasing evaporation by 5 percent produced only one year of "dry lakebed" conditions and increased the average lake volume considerably. The true values of evaporation were expected to vary from year to year but well within this +5 percent margin, based on evaporation from the pan near Davis Creek.

By removing the adjustment to precipitation which was applied during the 1946-1975 period to standardize the mean, "dry lakebed" conditions occurred six years whereas at the current adjusted level, "dry lakebed" conditions occurred during thirty years in seven episodes, the most recent of which began in 1920 and ended in 1939.

Increasing the runoff coefficient from 1.8 to 2.0 yielded only one "dry lakebed" year. Decreasing the coefficient to 1.6 produced 47 years of "dry lakebed" conditions in thirteen episodes. The choice of 1.8 is based on the premise that yield from ungaged drainage area is proportional to the average of the ten gaged subbasins. Despite the variability in runoff, the performance of this component in the 1946-1975 period underscored its choice as the most reasonable method of estimation.

The fact that the influence of each of these components is so delicately balanced between abundance and scarcity is one means of proof that the range of values chosen for these variable quantities was reasonable. A slight systematic error could skew the year-end volumes out of the range of expected values -- a situation easily detected in the recent series plots.

Each run of the program, regardless of the adjustments showed a sharp increase in projected lake volume toward the end of the series, coincidentally the period of increasing withdrawal. Since the model was calibrated for the 1940's and 1950's, due to regression between streamflow records made at that time, prior and subsequent values may have been over or underestimated, respectively, given the level of surface water consumption during the 1940's.

To correct this disparity, streamflow values from 1422 to 1900 were increased by an amount corresponding to irrigation consumptive use at the circa 1945 level. From 1900 to 1945, streamflow was augmented at a decreasing rate such that the 1940 to 1950 period needed minimal adjustment. Streamflow values subsequent to 1945 were reduced by a volume equal to consumptive water use after 1945. In this manner, withdrawal could be equilibrated over time and lake volume prior to 1900 should have become more realistic.

The value of this adjustment might, however, be slightly different from that applied to the 1946-1975 model due to the changed responses of those components which were now synthesized from tree-ring indices. The post-1945 level of irrigation is fairly well documented to be at the 25,000 acre-foot level based on an estimate of irrigation requirements (SCS 1978). Least-squares analysis between estimated and actual year-end volumes for this later period (1946-1964) yielded a correlation coefficient of 0.75, significant to the 0.99 level. Since the range of the observed volumes is much greater than the synthesized volumes, the fit is not very good although trends are parallelled well. Even so, a marked improvement in the correlation statistics was achieved in going from the component stage (generation of precipitation and runoff values) to the annual water budget stage.

Several runs were performed for a variety of estimated pre-1945 consumptive use figures. The first run used the 25,000 acre-foot figure for the pre-1945 period. By simply augmenting runoff by this amount an effective increase in runoff of 10 to 15 percent was effected. Consequently lake volumes became much higher than the unadjusted run with average volumes between 400 and 500,000 acre-feet compared to 250 to 300,000 acre-feet in the control (unadjusted) run. No "dry lakebed" years were noted.

The second run assumed a pre-1945 adjustment of 15,000 acre-feet and, accordingly, the average volumes decreased to between 300 and 350,000 acre-feet and produced only one "dry lakebed" year. A third run, using an adjustment of 10,000 acre-feet, further reduced volumes and produced three "dry lakebed" years with more recurrent low-water periods. A fourth run used a 5,000 acre-foot adjustment and yielded 9 "dry lakebed" years.

In order to accomodate the uncertainty associated with the pre-1945 adjustment, a separate probability analysis was prepared for each run to determine the recurrence interval of year-end lake volumes.

Probability Analysis of Lake Volumes

Although probability analysis of hydrologic time series is usually event-based, as in flood-frequency analysis, with each event assumed to be of short duration, analysis of extreme phenomena of variable duration is also practiced. The recent need to establish low-flow criteria on streams in many western states has required an analysis of not only the frequency of a given discharge but the duration of an average given discharge. The U.S. Geological Survey has begun to publish statistical summaries for gage sites which lists discharge values in a table of six recurrence interval values (2, 5, 10, 20, 50, 100 years) by the duration in consecutive days (1, 3, 7, 14, 30, 60, 90, 120, 183)(Friday and Miller 1984). The 7-day 80 percent exceedance probability (5 year recurrence) is the combination most commonly used to determine minimum flow at a stream site.

Applying this type of technique to Goose Lake year-end volumes requires changing the increment from days to years and the quantity from discharge to year-end lake volume. The Log-Pearson technique was used, as was done in the USGS report (1984) and recurrence intervals were calculated for each of the lake volume time series.

The first series tested assumed a 25,000 acre-foot correction prior to 1945. The volume which corresponded to the 99% exceedance probability, or 1 in 100 year chance was 104,259 acre-feet, well above the actual low levels observed in the 1920's and 1930's. The 200-year high volume value was 789,208 acre-feet. Skewness of the logs was -0.895 indicating an abundance of data in the upper range.

The second series, assuming a pre-1945 adjustment of 15,000 acre-feet possessed a 99% exceedance probability volume of 88,070 acre-feet and a 200-year high volume of

TABLE V

PROBABILITY DISTRIBUTION OF ANNUAL YEAR-END LAKE LEVEL, GOOSE LAKE, OREGON-CALIFORNIA

Exceedance Probability	Recurrence Interval (yrs.)	25000 AF correction	15000 AF correction	10000 AF correction	5000 AF correction	Actual data 1946-1975
0.990	1.01	104259	88070	80347	71408	157026
0.950	1.05	167241	135554	121964	107557	231780
0.900	1.11	209125	167376	149955	132086	281765
0.800	1.25	267205	212372	189820	167402	352948
0.700	1.43	313528	249277	222834	197031	412087
0.500	2.00	396403	318286	285497	254302	525209
0.300	3.33	483825	396489	358195	322576	658436
0.200	5.00	537079	447644	406849	369436	749052
0.100	10.00	609169	522395	479687	441454	887235
0.040	25.00	681264	605505	563387	527147	1050219
0.020	50.00	724059	660167	620188	587217	1163677
0.010	100.00	759512	709450	672722	644249	1270865
0.005	200.00	789208	754285	721720	698788	1372930
Skewness		-0.895	-0.611	-0.479	-0.360	-0.384
N		543	543	543	543	30

754,285. This adjusted series showed a slightly greater range of probable volumes. The third and fourth series contained decreasing maxima and minima as shown in Table V.

Also given in Table V is the probability distribution for the actual volumes, 1946 through 1975. Obvious are the much higher values for the recent period which did not include any drought years. The range of the values for the recent period best approximates that produced by the 25,000 acre-foot correction. Extremes were not well matched by the 25,000 acre-foot corrected series, but the recent period of record was not diverse enough to allow rigorous comparison. Given that the 25,000 acre-foot adjusted series was closest for all probabilities to those of the recent period, the assumption of the 25,000 acre-foot adjustment was accepted as being the closest approximation to consumptive use in the basin. This helped to underscore the values used to derive the original irrigation curve used for the 1946-1975 series.

Evaluation of Reconstructed Lake Volumes

The time series plot of lake volumes shown in Figure 19 was generated by the water-budget calculations adjusted for consumptive withdrawal at the 25,000 acre-foot level. Having verified that the reconstructed series did reasonably parallel the actual series for recent years (r=0.75) the time series plot may be examined as an index of water supply from 1422 to 1964.

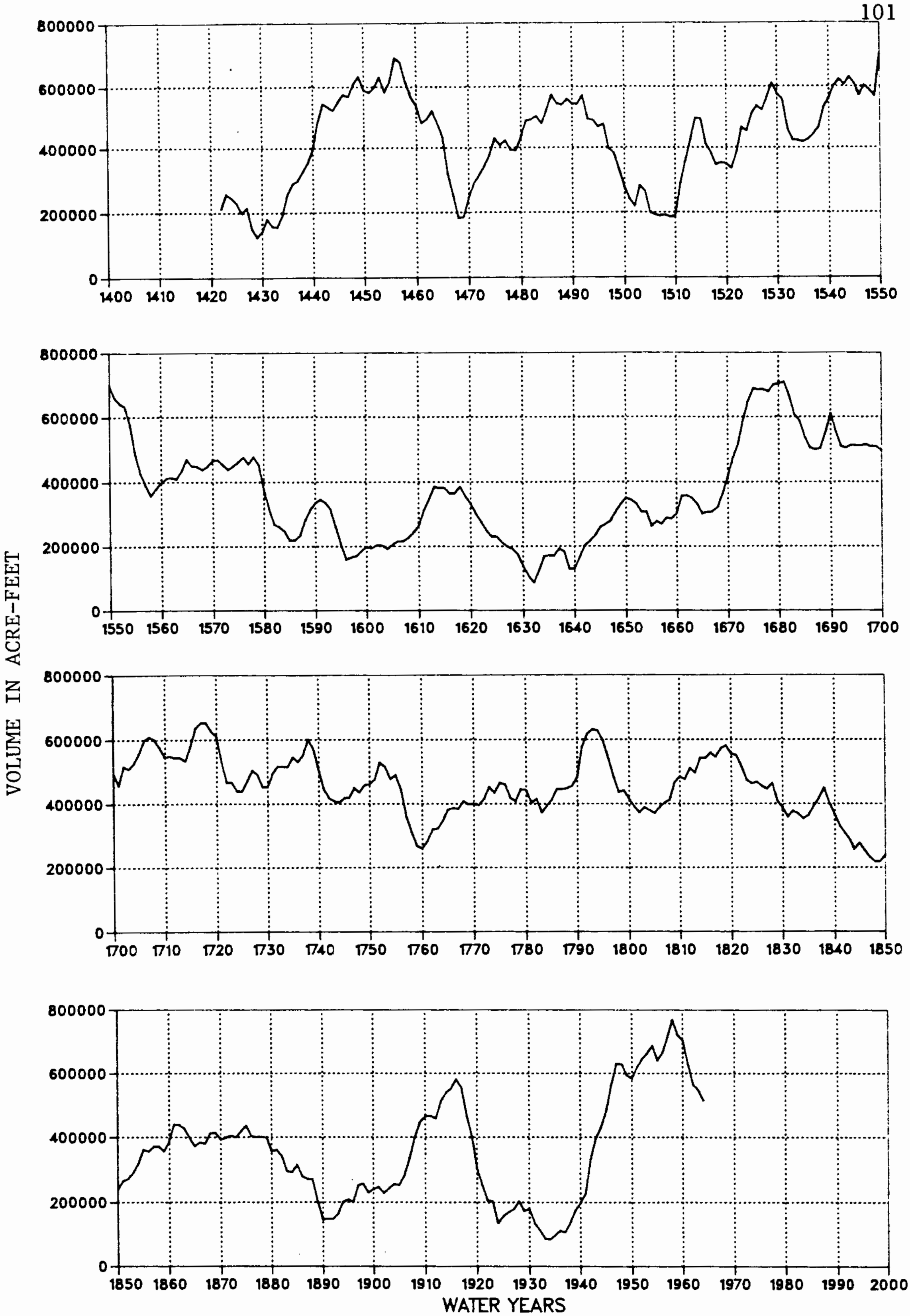

Figure 19. Time series plot of reconstructed lake levels, Goose Lake, 1422 to 1964.

Daum (1966) prepared an historical documentary of lake levels in the Goose Lake Basin from the 1830s to the present. He indicated that when the lake surface was below 4696 feet (140,000 acre-feet volume) that this implied visibly low water conditions, but not quite the "dry lakebed" conditions referred to earlier. Annual values (listed in the Appendix) which were estimated to be below this volume were marked with a flag signifying low water conditions. Only three episodes of critical low water occur in the reconstructed record -- the late 1420's- early 1430's, the mid-1630's, and the 1925 to 1939 period. From this record it may be interpreted that the most recent low water period was the longest in the 543 years prior to 1964, with nine years' volume less than 140,766 acre-feet. The 1630's were almost as dry with four consecutive years of less than 140,766 acre-feet volume, although there were fifteen years of less than 200,000 acre-feet volume. The 1428-1434 low water period does not appear to have been as severe, with only one year at less than 140,766 acre-feet. This suggests that Goose Lake basin experienced severe water deficits of five years or greater duration only three times in the last 543 years.

The reconstructed series does not replicate high water years faithfully due to the greater sensitivity of trees to drought. It is noteworthy that no simulated overflow phenomena occurred in any of the separate runs despite suggestions that Goose Lake has been high enough to do so several times in the past.

A compilation of historical basin conditions by Daum (1966) presents further corroboration of the reconstructed series. The earliest entry is the 1801 to 1828 period, which he identified as having been wet. A corresponding positive trend is apparent in the time series plot for this period. Other wetter or high water periods listed correspond to relative maxima in the reconstructed record, although not to the near overflow levels reported. Reported drought spells (1839-1844, 1885-1889, 1924-1934) correspond very well with extreme downturns in reconstructed lake volumes although the literal volumes are not so reliable as the relative series depicted in the time series plot. Given the extent of historical knowledge of the lake, this reconstructive method of water-budget analysis appears to have been a reliable means of depicting long-term fluctuation in Goose Lake, albeit more a series of relative levels than literal levels due to the specific environmental indices to which trees are most sensitive.

CHAPTER VI

REFLECTIONS ON LAKE VOLUME MODELLING

Summary

From the experience gained in this project, the modelling of annual lake volumes using the mass-balance approach can be done reliably and repetitively for a series of years, even with a significant amount of synthesized or interpretive component data. The first portion of the thesis was the modelling of Goose Lake year-end volumes for the period 1946-1975. Precipitation data were obtained from Lakeview, Oregon, located less than ten miles from the lake surface. Evaporation values were estimated via the Thornthwaite potential evapotranspiration method calibrated against an evaporation pan which was operated in the basin for several years. Surface to volume relationships were defined for the lake such that precipitation and evaporation volumes could be evaluated more carefully.

Streamflow records were obtained for all gaging stations in the basin. The short period of record for these stations required that annual flow be regressed against the common period with a longer-term site (Cottonwood Creek) so that a longer record could be synthesized. For ungaged areas, runoff per unit area was assumed to be roughly equal to the average discharge of the gaged areas. This discharge volume was a coefficient applied to the known gaged discharge in the basin for each given year.

By adding the positive components of precipitation and streamflow to the antecedent lake volume and subtracting the evaporated volume year-end lake volumes were obtained which well approximated the observed volumes ($r=0.97$, $r^2=0.93$). Even a self-generating series (corrected for withdrawals) -- which required only the first year's antecedent volume -- produced a highly confident reconstruction, explaining 88 percent of the variance of the original process ($r=0.94$).

The success of this procedure has shown that even with synthesized streamflow and evaporation estimates and a less than perfect estimate of consumptive withdrawal, a highly reliable volumetric series can be generated for closed-basin lakes. Fortunately, lake-level observations and stream-gaging were extensive enough to produce several components of sufficient accuracy to ensure the success of the model application.

This first demonstration was crucial to the second portion of the thesis -- can a long-term environmentally sensitive series be used to reconstruct components of the water balance on an annual basis? The obvious choice for such an environmentally sensitive series was tree rings which have been used to reconstruct both precipitation and streamflow by many authors. This project, however, is the first time anyone has used both precipitation and streamflow values reconstructed from tree rings as primary inputs into a water budget model.

The initial comparison between the individual tree-ring indices, collected and prepared by the University of Arizona Laboratory of Tree-Ring Research, and corresponding precipitation and runoff values for the common period (1913-1964) did not yield high correlations. The development of cumulative departure curves for all three series, however, revealed a highly synchronous behavior between the three. The shape of the curves is remarkably similar and illustrates the trees' sensitivity to moisture changes manifest both in the precipitation and runoff series.

Regression equations were developed to relate the annual slope of the cumulative departure curves for precipitation and runoff to that of the tree rings. Although the correlation coefficients were low on an annual basis (r=0.44 to 0.56) the similarity between the cumulative departure series from which they were derived was high (r=0.75 to 0.92). This indicates that although the prediction accuracy for a given year may be low the trend sensitivity is still high.

The long-term lake-volume series was reconstructed for the period 1422 to 1964 on the basis of the mass balance component relationship developed for the 1946-1975 period except that precipitation and runoff values were synthesized and evaporation was constant at an average value observed in the 1946-1975 run. The accuracy of reconstructing annual values improved (for the recent common period, 1946-1964 such that the correlation coefficient between actual and reconstructed values was 0.75. The historical record of wet and dry basin conditions (since 1800) was replicated to a high degree by the model, but the process was decidedly more sensitive to low- than high-water events. Although the accuracy of reconstructing annual volumes using tree rings was much lower than was achieved for the carefully modelled 1946-1975 period, the use of tree-ring data in the synthesis of volumetric time series does provide an index of water availability -- albeit biased toward drought -- for several hundred years in the Goose Lake basin.

Observations and Recommendations

Several specific observations were drawn in relation to volumetric modelling and the application of tree-ring data to the reconstruction model used. First, annual volumetric modelling can be fairly successful, even with a sizeable portion of synthesized inputs, as was the case in the 1946-1975 period. Assumptions and methodology used in the development of the model should be applicable in the determination of water balance for other closed basins within the region. Harney-Malheur Lake, of particular concern now due to its recent high volume, seems particularly well suited for an intensive water budget analysis of this type. Although more data on various components (irrigation, evaporation, actual streamflow contribution to the lake) may be required at Malheur-Harney Lake, a more detailed volumetric time series should show the recent events to be well explained by the interaction of the inflow and loss components.

Annual lake volume is very sensitive to all components, as was revealed when each component was varied independently. While the form of the time series was similar, the cumulative effects of marginal incremental or decremental change for all components was sizeable. Thus the practice of using an assumed "average" value, such as evaporation, throughout the time series is discouraged. Average or non-varying component values act to dampen the series sensitivity and make the outcome less like the natural response. The use of average evaporation in the long-term reconstruction was unavoidable because no consistent relationship could be derived between precipitation and temperature, the primary index of evaporation potential.

The use of tree rings in the reconstruction of streamflow and precipitation is more sensitive to drought than to surplus water. This reduces the accuracy of the reconstructed series such that it acts more like an index of water shortage or relative abundance than as an accurate volumetric predictor. A more rigorous tree-ring to runoff relationship could be developed if many more tree ring sites were established within the basin, each sensitive to local environmental peculiarities. As Stockton (1975) demonstrated, correlations improve with a larger number of tree ring sites over a larger drainage area. This way drainage idiosyncracies of each subbasin become less significant to the total basin discharge and the discharge values are smoothed to better approximate the inherently smoothed tree-ring series.

From the reconstructed record it appears that increasing withdrawal in the post-1945 period has reduced lake levels which may have been higher under natural streamflow conditions. Daum (1966) and Phillips and VanDenburgh (1971) have supported this view noting that overflow phenomena are not likely to occur again given the present level of water resource development. Although this practice will reduce the possibility of flooding of former lakebed acreage, it will also increase the likelihood of dry lakebed conditions during drier periods.

According to the reconstructed volume series it appears that "low water" conditions (less than 140,000 acre-feet) occurred three times in the last 560 years with a duration of about 5 years' length. These periods were the

1430s, the 1630s, and the 1930s. The most recent "low water" period (1920's-30's) was exacerbated by withdrawals which led to decreased streamflow contribution to the lake. Low water or dry lakebed conditions do not impact water-use patterns in the basin because there are no withdrawals directly from the lakebody. The impact upon the migratory birds which use the lake as a major stop on the north-south flyway is undetermined but is not likely to be beneficial.

In conclusion, the thesis -- that a reliable annual lake volume model can be easily constructed given a number of carefully estimated components -- has been proven true. The corollary thesis -- that tree rings can be used to drive such a model -- was shown to be partially true in that a relative series of lake volumes can be constructed which depicts trends rather than absolute annual volumes. Given more abundant local tree-ring data, such a relationship might be improved. Despite its shortcomings, the modelling process should be tested in nearby basins for evaluation of currently apparent water budget problems.

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Appendix A. Program AUTOMASTER.BASIC, used to estimate year-end volumes given precipitation, antecedent volume/area, streamflow, and evaporation. Program does not include section on consumptive withdrawal calculation used for final time series plot.

```
100 !-----------------------------------------------
110 ! FUNCTION TO TRUNCATE TO FIELD LENGTH AND DECIMALS
120 DEF FNG$(G1,G2,G3)
130      G4=G1
140      G5=(INT(G4*10**G2+0.5))/(10**G2)
150     G6$=STR$(G5)
160 IF G2=0 THEN 300
170 G6=INDEX(G6$,'.',1)
180 IF G6=0 THEN DO
190 G6$=G6$+'.'
200 FOR G8=1 TO G2
210 G6$=G6$+'0'
220 NEXT G8
230 GOTO 300
240 DOEND
250 G7=LEN(RIGHT(G6$,G6+1))
260 IF G7=>G2 THEN 300
270 FOR G8=1 TO G2-G7
280 G6$=G6$+'0'
290 NEXT G8
300      IF LEN(G6$)= G3 THEN 350
310      IF LEN(G6$)>G3 THEN G6$=LEFT(G6$,G3)
320      IF LEN(G6$)<G3 THEN DO
330      G6$=' '+G6$ UNTIL LEN(G6$)=G3
340      DOEND
350     FNG$=G6$
360 FNEND
370 !
380 I=1
381 !-----------------------------------------------
382 DEFINE FILE #1='CTN.LS'
383 DEFINE FILE #2='PRCP.LS'
384 DEFINE FILE #3='TEXT'
385 DEFINE FILE #4='LEVELS'
386 DIM Y(600),V0(600),V9(600),P(600)
390 !-----------------------------------------------
400 !
410 INPUT'SURFACE ELEVATION OR VOLUME (E OR V)=';E$
420 IF E$='E' THEN 790
430 INPUT'VOLUME=';V9
440 !*************************************************
450 !
460 IF V9<140219 THEN 540
470 IF V9=>140219 AND V9<213567 THEN 570
490 IF V9=>213567 AND V9<294446 THEN 630
500 IF V9=>294446 AND V9<379912 THEN 660
510 IF V9=>379912 AND V9<469573 THEN 690
520 IF V9=>469573 AND V9<861191 THEN 720
530 IF V9=>861191 THEN 750
540 E=((V9+41632.6999)/425.7277)**(1/3)+4688.4306
550 A=1277.1833*(E-4688.4306)**2
560 GOTO 1030
570 E=((V9+94687.917)/205.4324)**(1/3)+4685.543
580 A=616.297*(E-4685.543)**2
590 GOTO 1030
600 E=((V9+150479.19715)/134.145454)**(1/3)+4683.0593656
610 A=402.4363643*(E-4683.0593656)**2
620 GOTO 1030
630 E=((V9+563798.7974)/29.366920)**(1/3)+4667.2051423
640 A=88.1007608*(E-4667.2051423)**2
```

```
650 GOTO 1030
660 E=((V9+933066.7435)/14.349516)**(1/3)+4653.9456527
670 A=43.0485491*(E-4653.9456527)**2
680 GOTO 1030
690 E=((V9+752942.5264)/19.278412)**(1/3)+4660.1295382
700 A=57.8352375*(E-4660.1295382)**2
710 GOTO 1030
720 E=((V9+1026184.5962)/12.87579)**(1/3)+4651.2134621
730 A=38.6273624*(E-4651.2134621)**2
740 GOTO 1030
750 E=((V9+4954009.3033)/1.362592)**(1/3)+4541.7341797
760 A=4.087781*(E-4541.7341797)**2
770 !*******************************************************
780 GOTO 1030
790 INPUT'SURFACE ELEVATION (FEET MSL)=';E
800 IF E<4697 THEN 860
810 IF E=>4697 AND E<4698 THEN 890
820 IF E=>4698 AND E<4699 THEN 920
830 IF E=>4699 AND E<4700 THEN 950
840 IF E=>4700 AND E<4704 THEN 980
850 IF E=>4704 THEN 1010
860 A=402.4363643*(E-4683.0593656)**2
870 V9=134.145454*(E-4683.05936)**3-150479.19715
880 GOTO 1030
890 A=88.1007608*(E-4667.2051423)**2
900 V9=29.366920*(E-4667.2051423)**3-563798.7974
910 GOTO 1030
920 A=43.0485491*(E-4653.9456527)**2
930 V9=14.349516*(E-4653.9456527)**3-933066.7435
940 GOTO 1030
950 A=57.8352375*(E-4660.1295382)**2
960 V9=19.278412*(E-4660.1295382)**3-752942.5264
970 GOTO 1030
980 A=38.6273624*(E-4651.2134621)**2
990 V9=12.87579*(E-4651.2134621)**3-1026184.5962
1000 GOTO 1030
1010 A=4.087781*(E-4541.7341797)**2
1020 V9=1.362592*(E-4541.7341797)**3-4954009.3033
1030 !
1040 IF V9=>2257107 THEN V9=2257107    !MAX VOLUME
1050 IF A=>124140 THEN A=124140    !MAX AREA
1060 IF V9=>2257107 THEN D$='OVERFLOW'
1070 IF V9<2257107 THEN D$=' '
1080 IF V9<79066 THEN E$='DRY LAKEBED'
1090 IF V9=>79066 THEN E$=' '
1130 !-------------------------------------------
1140 !
1150 !   THIS SEGMENT RETRIEVES COTTONWOOD RUNOFF
1160 !
1180 READLINE #1,A$
1190 ON END #1 GOTO 2220
1200 Y=VAL(SUB(A$,1,4))    !EXTRACTS YEAR FROM RUNOFF RECORD
1210 X=VAL(SUB(A$,43,49))  !EXTRACTS ACRE-FEET OF RUNOFF
1220 !
1230 !-------------------------------------------
1240 !
1250 !   THIS SEGMENT ASSIGNS AND CALCULATES STREAMFLOW
1260 !      DEPENDENT UPON REGRESSION EQUATIONS AGAINST
1270 !      COTTONWOOD RECORD
1280 !
```

```
1290 ! S0 = BAUERS CREEK R**2 = 0.9127 SIG TO 0.99
1300 S0=0.850748*X+965.378
1310 ! S1 = CAMP CREEK     R**2 = 0.7833 NOT SIG TO 0.95
1320 S1=0.183051*X+1542.702
1330 ! S2 = COTTONWOOD CR., CAL   R**2 = 0.501  SIG TO 0.95
1340 S2=9.619575*(X**0.5414187)
1350 ! S8 = DAVIS CREEK, CAL   R**2 = 0.4667  SIG TO 0.95
1360 S8=4.375462*(X**0.7769977)
1370 ! S3 = DREWS CREEK    R**2 = 0.8262   SIG TO 0.99
1380 S3=3.658392*X-16629.3947
1390 ! S4 = DRY CREEK      R**2 = 0.8957   SIG TO 0.99
1400 S4=0.623512*X-293.609
1410 ! S5 = LASSEN CREEK, CAL   R**2 = 0.8645
1420 S5=0.57355*X+1831.064
1430 ! S6 = NEW PINE CREEK, CAL-OR   R**2 = 0.2544   NOT SIG
1440 S6=0
1450 ! S7 = THOMAS CREEK        R**2 = 0.933  SIG TO 0.99
1460 S7=0.67512*X+1108.34
1470 ! S9 = WILLOW CREEK, CAL      R**2 = 0.7119
1480 S9=0.40831*X+1089.876
1490 !
1500 IF S0<0 THEN S0=0
1510 IF S1<0 THEN S1=0
1520 IF S2<0 THEN S2=0
1530 IF S3<0 THEN S3=0
1540 IF S4<0 THEN S4=0
1550 IF S5<0 THEN S5=0  ! THIS AVOIDS NEGATIVE FLOW
1560 IF S6<0 THEN S6=0
1570 IF S7<0 THEN S7=0
1580 IF S8<0 THEN S8=0
1590 IF S9<0 THEN S9=0
1600 !
1610 !--------------------------------------------
1620 !
1630 WRITE #3,'*******************************************'
1640 WRITE #3,'CALCULATED RUNOFF FROM BASIN'
1650 WRITE #3,'           ';Y
1660 WRITE #3
1670 WRITE #3,'COTTONWOOD CREEK, OR=';X
1680 WRITE #3,'BAUERS CREEK=';S0
1690 WRITE #3,'CAMP CREEK=';S1
1700 WRITE #3,'COTTONWOOD CR., CA=';S2
1710 WRITE #3,'DAVIS CREEK=';S8
1720 WRITE #3,'DREWS CREEK=';S3
1730 WRITE #3,'DRY CREEK=';S4
1740 WRITE #3,'LASSEN CREEK=';S5
1750 WRITE #3,'THOMAS CREEK=';S7
1760 WRITE #3,'WILLOW CREEK=';S9
1770 WRITE #3,'-------------------------------------------'
1780 !
1790 !------------------------------------------
1800 !
1810 ! THIS SEGMENT READS IN CLIMATIC VARIABLES
1820 !
1830 READLINE #2,A$
1840 P(I)=VAL(SUB(A$,22,26))  !EXTRACTS PRECIP ESTIMATE
1850 P=P(I)
1860 E1=41.21        !CORRECTED AVERAGE EVAPORATION FROM LAKE SURFACE
1870 !
1880 !-------------------------------------------------
```

```
1890 !
1900 ! AREA AND VOLUME TRANSFORMATION
1910 P1=P/12 ! PORTION OF A FOOT
1920 P1=P1*A  ! ACRE-FEET OF POTENTIAL PRECIP
1930 E1=E1/12  !PORTION OF FOOT
1940 E1=E1*A   !ACRE-FEET OF EVAP POTENTIAL
1950 S=S0+S1+S2+S3+S4+S5+S6+S7+S8+S9+X  ! SUM OF STREAMFLOWS
1960 S=S*1.8  !CORRECTION FOR LOWLAND AREAS NOT
1970 !          COVERED IN PREVIOUSLY MENTIONED DRAINAGES.
1980 !
1990 !    CALCULATION OF WATER BALANCE
2000 !V0 = PREDICTED END VOLUME
2010 !
2020 V0=V9+S+P1-E1   !THE TRIUMPHANT FINAL PRODUCT
2030 !
2045 V9(I)=V9
2046 V0(I)=V0
2048 Y(I)=Y
2050 WRITE #3
2052  !V1=V0*0.9455)+10499 CORRECTION TURNED OFF
2060 WRITE #3,'     ANTECEDENT VOLUME=':FNG$(V9(I),0,7):'ACRE-FEET':D$:E$
2070 WRITE #3,'     CALCULATED RUNOFF =';FNG$(S,0,7):'ACRE-FEET'
2080 WRITE #3
2090 WRITE #3,'     PRECIPITATION ESTIMATE =';P:'INCHES'
2100 WRITE #3,'             VOLUME ADDED TO LAKE =':FNG$(P1,0,7):'ACRE-FEET'
2110 WRITE #3,'     EVAPORATION FROM LAKE SURFACE = 41.21 INCHES'
2120 WRITE #3,'             VOLUME EVAPORATED =':FNG$(E1,0,7):'ACRE-FEET'
2130 WRITE #3
2140 WRITE #3,'     CALCULATED END VOLUME =':FNG$(V0,0,7):'ACRE-FEET'
2160 WRITE #3
2170 WRITE #3,'**********************************************************'
2180 WRITE #4, Y(I), FNG$(V9(I),0,7),FNG$(V0(I),0,7):D$:E$
2190 I=I+1
2200 V9(I)=V0(I-1)
2205 V9=V9(I)
2210 GOTO 450
2220 CLOSE #1
2230 CLOSE #2
2240 CLOSE #3
2250 CLOSE #4
2260 END
```

Appendix B. Annual lake volumes for Goose Lake, Oregon-California for the years 1422 to 1964. This dataset is displayed in Figure 19. Integers displayed imply greater accuracy than can be obtained. Values should be read to the nearest 10 thousand acre-feet.

Year	Beginning Volume AF	Year-end Volume AF
1422	250000	212398
1423	212398	257811
1424	257811	245984
1425	245984	229349
1426	229349	198635
1427	198635	216096
1428	216096	150688
1429	150688	124422
1430	124422	143307
1431	143307	182007
1432	182007	158640
1433	158640	156164
1434	156164	192236
1435	192236	255740
1436	255740	288234
1437	288234	298717
1438	298717	326567
1439	326567	354921
1440	354921	395911
1441	395911	486218
1442	486218	546359
1443	546359	535541
1444	535541	524030
1445	524030	552573
1446	552573	576806
1447	576806	568488
1448	568488	609069
1449	609069	633562
1450	633562	591134
1451	591134	581474
1452	581474	597744
1453	597744	632217
1454	632217	582735
1455	582735	616755
1456	616755	692641
1457	692641	677203
1458	677203	614259
1459	614259	566535
1460	566535	537748
1461	537748	479764
1462	479764	494761
1463	494761	522437
1464	522437	478452
1465	478452	433600
1466	433600	317058
1467	317058	252100
1468	252100	181923
1469	181923	186735
1470	186735	244152
1471	244152	288502
1472	288502	314271
1473	314271	342239
1474	342239	375896
1475	375896	430326
1476	430326	407061
1477	407061	423225
1478	423225	393881
1479	393881	390782
1480	390782	431461
1481	431461	488449

1482	488449	493816
1483	493816	505710
1484	505710	477541
1485	477541	526124
1486	526124	574021
1487	574021	546337
1488	546337	540886
1489	540886	560831
1490	560831	545085
1491	545085	543296
1492	543296	571905
1493	571905	494350
1494	494350	490315
1495	490315	465465
1496	465465	476593
1497	476593	398392
1498	398392	382590
1499	382590	330638
1500	330638	277858
1501	277858	240571
1502	240571	218044
1503	218044	283112
1504	283112	265420
1505	265420	199650
1506	199650	191594
1507	191594	188764
1508	188764	192197
1509	192197	185758
1510	185758	188851
1511	188851	286926
1512	286926	357191
1513	357191	423755
1514	423755	497269
1515	497269	494668
1516	494668	412794
1517	412794	384763
1518	384763	346377
1519	346377	353772
1520	353772	350074
1521	350074	334707
1522	334707	384572
1523	384572	463971
1524	463971	452366
1525	452366	512294
1526	512294	538372
1527	538372	523049
1528	523049	565875
1529	565875	610314
1530	610314	575557
1531	575557	558408
1532	558408	458992
1533	458992	423392
1534	423392	423737
1535	423737	416995
1536	416995	426822
1537	426822	442456
1538	442456	463221
1539	463221	532545
1540	532545	562118
1541	562118	601513

1542	601513	623119
1543	623119	605054
1544	605054	629916
1545	629916	609455
1546	609455	571120
1547	571120	604365
1548	604365	588060
1549	588060	567989
1550	567989	699470
1551	699470	661580
1552	661580	641777
1553	641777	632843
1554	632843	576032
1555	576032	485507
1556	485507	425850
1557	425850	389209
1558	389209	357242
1559	357242	378992
1560	378992	396820
1561	396820	410753
1562	410753	414310
1563	414310	408715
1564	408715	433410
1565	433410	469235
1566	469235	448274
1567	448274	447339
1568	447339	436021
1569	436021	447093
1570	447093	465624
1571	465624	467930
1572	467930	452342
1573	452342	436937
1574	436937	447902
1575	447902	461072
1576	461072	476209
1577	476209	454563
1578	454563	477442
1579	477442	452084
1580	452084	376931
1581	376931	317001
1582	317001	269241
1583	269241	260650
1584	260650	246626
1585	246626	218053
1586	218053	219463
1587	219463	234091
1588	234091	279967
1589	279967	313810
1590	313810	334988
1591	334988	347005
1592	347005	335409
1593	335409	314727
1594	314727	260318
1595	260318	205688
1596	205688	157890
1597	157890	165572
1598	165572	169669
1599	169669	184960
1600	184960	198393
1601	198393	192539

1602	192539	204284
1603	204284	202596
1604	202596	189889
1605	189889	204473
1606	204473	216100
1607	216100	216202
1608	216202	226308
1609	226308	243180
1610	243180	264083
1611	264083	312176
1612	312176	347183
1613	347183	385435
1614	385435	379918
1615	379918	382073
1616	382073	364841
1617	364841	365073
1618	365073	386014
1619	386014	356157
1620	356157	333170
1621	333170	302437
1622	302437	276944
1623	276944	250062
1624	250062	229312
1625	229312	230586
1626	230586	211447
1627	211447	198195
1628	198195	190785
1629	190785	173328
1630	173328	137571
1631	137571	108371
1632	108371	86048
1633	86048	124527
1634	124527	167526
1635	167526	172314
1636	172314	169938
1637	169938	193325
1638	193325	183053
1639	183053	129283
1640	129283	130288
1641	130288	164645
1642	164645	201846
1643	201846	216308
1644	216308	233075
1645	233075	258922
1646	258922	268880
1647	268880	278998
1648	278998	307947
1649	307947	331420
1650	331420	350746
1651	350746	343938
1652	343938	332678
1653	332678	307187
1654	307187	306789
1655	306789	261904
1656	261904	278226
1657	278226	268184
1658	268184	288554
1659	288554	285307
1660	285307	303034
1661	303034	356073

1662	356073	359002
1663	359002	349537
1664	349537	332467
1665	332467	301814
1666	301814	307158
1667	307158	308512
1668	308512	323360
1669	323360	365795
1670	365795	416025
1671	416025	472942
1672	472942	514927
1673	514927	590272
1674	590272	648675
1675	648675	687762
1676	687762	683696
1677	683696	685377
1678	685377	677828
1679	677828	700007
1680	700007	703857
1681	703857	709212
1682	709212	665015
1683	665015	606876
1684	606876	586759
1685	586759	538090
1686	538090	504984
1687	504984	498121
1688	498121	502572
1689	502572	550727
1690	550727	610646
1691	610646	554273
1692	554273	508836
1693	508836	503413
1694	503413	512601
1695	512601	512142
1696	512142	509930
1697	509930	514982
1698	514982	507160
1699	507160	508948
1700	508948	494650
1701	494650	456996
1702	456996	518202
1703	518202	508353
1704	508353	527728
1705	527728	557734
1706	557734	597512
1707	597512	610506
1708	610506	600860
1709	600860	575903
1710	575903	546208
1711	546208	549678
1712	549678	543912
1713	543912	545777
1714	545777	533289
1715	533289	578747
1716	578747	636293
1717	636293	653062
1718	653062	653884
1719	653884	627597
1720	627597	610954
1721	610954	531124

1722	531124	466728
1723	466728	467106
1724	467106	439297
1725	439297	439433
1726	439433	471092
1727	471092	504425
1728	504425	492375
1729	492375	453158
1730	453158	451643
1731	451643	494183
1732	494183	516592
1733	516592	517488
1734	517488	514768
1735	514768	545942
1736	545942	529892
1737	529892	552637
1738	552637	601767
1739	601767	571409
1740	571409	506432
1741	506432	444595
1742	444595	417860
1743	417860	408357
1744	408357	403488
1745	403488	418403
1746	418403	419348
1747	419348	449750
1748	449750	434660
1749	434660	458112
1750	458112	461302
1751	461302	476413
1752	476413	528677
1753	528677	514286
1754	514286	476470
1755	476470	489991
1756	489991	445765
1757	445765	360926
1758	360926	311516
1759	311516	267816
1760	267816	259455
1761	259455	282908
1762	282908	319768
1763	319768	323167
1764	323167	346792
1765	346792	381670
1766	381670	387062
1767	387062	383116
1768	383116	409110
1769	409110	397209
1770	397209	400714
1771	400714	395091
1772	395091	416131
1773	416131	452152
1774	452152	433272
1775	433272	465633
1776	465633	460929
1777	460929	418061
1778	418061	406840
1779	406840	445684
1780	445684	443357
1781	443357	402708

1782	402708	415940
1783	415940	371818
1784	371818	393830
1785	393830	413350
1786	413350	446220
1787	446220	445530
1788	445530	448414
1789	448414	456241
1790	456241	482424
1791	482424	578116
1792	578116	617859
1793	617859	632682
1794	632682	628171
1795	628171	597030
1796	597030	543768
1797	543768	486911
1798	486911	435881
1799	435881	441698
1800	441698	415322
1801	415322	390448
1802	390448	372163
1803	372163	388929
1804	388929	379524
1805	379524	369610
1806	369610	390083
1807	390083	403121
1808	403121	412840
1809	412840	466643
1810	466643	484640
1811	484640	476220
1812	476220	510884
1813	510884	496398
1814	496398	543309
1815	543309	541687
1816	541687	559742
1817	559742	545908
1818	545908	572480
1819	572480	582435
1820	582435	555673
1821	555673	551149
1822	551149	516772
1823	516772	475094
1824	475094	462290
1825	462290	468489
1826	468489	454634
1827	454634	445947
1828	445947	464610
1829	464610	408965
1830	408965	386669
1831	386669	358486
1832	358486	378433
1833	378433	368636
1834	368636	352915
1835	352915	364812
1836	364812	392732
1837	392732	417595
1838	417595	449978
1839	449978	403212
1840	403212	367673
1841	367673	331302

1842	331302	307651
1843	307651	286658
1844	286658	256445
1845	256445	276993
1846	276993	253497
1847	253497	232174
1848	232174	217842
1849	217842	217656
1850	217656	239255
1851	239255	265852
1852	265852	273066
1853	273066	291030
1854	291030	319815
1855	319815	362610
1856	362610	356196
1857	356196	371184
1858	371184	372506
1859	372506	356363
1860	356363	386835
1861	386835	440085
1862	440085	438428
1863	438428	426416
1864	426416	398457
1865	398457	372237
1866	372237	385551
1867	385551	380020
1868	380020	413289
1869	413289	414850
1870	414850	391818
1871	391818	399434
1872	399434	406132
1873	406132	399845
1874	399845	418654
1875	418654	436938
1876	436938	404099
1877	404099	399749
1878	399749	401171
1879	401171	398956
1880	398956	357028
1881	357028	361618
1882	361618	341542
1883	341542	296053
1884	296053	291741
1885	291741	315347
1886	315347	279797
1887	279797	271155
1888	271155	270692
1889	270692	202324
1890	202324	146018
1891	146018	149596
1892	149596	148204
1893	148204	163680
1894	163680	201307
1895	201307	209250
1896	209250	200322
1897	200322	252223
1898	252223	258231
1899	258231	229363
1900	229363	240673
1901	240673	247970

1902	247970	228160
1903	228160	243061
1904	243061	256670
1905	256670	252352
1906	252352	283665
1907	283665	336870
1908	336870	400924
1909	400924	447585
1910	447585	465700
1911	465700	467178
1912	467178	457323
1913	457323	512978
1914	512978	538257
1915	538257	551901
1916	551901	581489
1917	581489	554323
1918	554323	466775
1919	466775	403800
1920	403800	304795
1921	304795	253618
1922	253618	206528
1923	206528	202858
1924	202858	134610
1925	134610	157159
1926	157159	170205
1927	170205	178464
1928	178464	203919
1929	203919	172789
1930	172789	179907
1931	179907	135320
1932	135320	112785
1933	112785	86342
1934	86342	84072
1935	84072	98450
1936	98450	112412
1937	112412	106323
1938	106323	137233
1939	137233	174750
1940	174750	198469
1941	198469	226690
1942	226690	332447
1943	332447	396333
1944	396333	430974
1945	430974	480425
1946	480425	562252
1947	562252	630894
1948	630894	629906
1949	629906	593475
1950	593475	582379
1951	582379	619114
1952	619114	646099
1953	646099	664161
1954	664161	688449
1955	688449	640532
1956	640532	665827
1957	665827	713001
1958	713001	769762
1959	769762	722050
1960	722050	704457
1961	704457	630739
1962	630739	564294
1963	564294	547399
1964	547399	514585